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Forage Legumes for Energy-Efficient Animal Production

Proceedings of a Trilateral Workshop Held in Palmerston North, New Zealand, April 30-May 4, 1984

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Preface

One-third of the fossil fuel and electrical energy used on farms in Australia, New Zealand, and the United States is consumed in the manufacture of fertilizers. About 50 percent of this energy is used in the manufacture of nitrogenous fertilizers in the three countries, which amounted to 9,890,145 metric tons in 1978-79 (FAO 1979). The majority (97.6 percent) of this energy was used in the United States, 2.2 percent in Australia, and 0.2 percent in New Zealand.

The inclusion of a forage legume in crop rotations can reduce the need for nitrogen fertilizer and is now the method by which nitrogen is supplied to most of the grain crops of the Mediterranean zones of Australia. The symbiosis between a legume and its appropriate Rhizobium can fix 100-200 kg N/ha/year. Much of this nitrogen is needed by the host plant, but the excess becomes incorporated in the soil-plant system and is available for the following grain crop.

The energy efficiency of forage legumes in animal production systems is not restricted to their symbiotic nitrogen fixation. Ruminants that graze or consume conserved forage legumes compared with grasses generally display faster growth and better production. This is partly because legume-fed ruminants consume more digestible energy and make more efficient use of the absorbed nutrients.

Unfortunately, legumes are more difficult to grow and maintain than grasses and there are relatively few parts of the world where legume-based grazing systems predominate in commercial practice. The great potential of legumes for improving energy efficiency can be realized on a wider scale only by analysis of successful and unsuccessful legume-based systems and by an appraisal and dissemination of the research findings that underpin these systems. An understanding of these systems requires expertise in various disciplines including bacteriology, genetics, agronomy, digestive physiology, and veterinary medicine.

The development of energy-efficient animal production systems through exploitation of forage legumes was the topic of discussion during a 5-day workshop held in Palmerston North, New Zealand, from April 30 to May 4, 1984. The workshop was arranged under the auspices of the Australia/United States of America Agreement for Scientific and Technical Cooperation and the New Zealand/United States of America Science and Technology Agreement. The New Zealand Department of Scientific and Industrial Research, Grasslands Division, Palmerston North, New Zealand, hosted the workshop.

The overall purpose of the workshop was to review and discuss the underlying research principles and philosophies concerning the adaptation, production, utilization, and improvement of forage legumes in energy-efficient livestock production systems and to identify research priorities. Specific objectives of the workshop were to:

1. Review ecological and edaphic constraints to forage legume adaptation, persistence, and production in diverse ecosystems and approaches to minimize these constraints.

2. Define approaches for plant germplasm development and breeding programs that will lead to improvements in the persistence, production, and utilization of promising forage legume species.

3. Formulate research approaches that will lead to innovative methods for use of forage legumes in ruminant livestock production systems.

4. Define problems and formulate research approaches to allow comparison of economic and energy budgeting of forage management systems that are legume-based, as opposed to nitrogen-fertilized grass-based.

5. Define future research cooperation and exchanges among scientists in Australia, New Zealand, and the United States that will lead to solutions to these problems.

The number of scientists attending the workshop was restricted in order to promote maximum discussion. Delegates were chosen from universities and State and Federal research institutions.

This book contains the papers presented at the workshop and the summaries of the discussions following the presentations. Editing of the manuscripts and discussions was the responsibility of the editorial committee members from the respective countries. The unique style of individual writers was generally retained with no attempt to enforce excessive conformity to phraseology and spelling.

During the workshop, specific recommendations for collaborative research projects among scientists from the three countries were developed. Scientists in the three participating countries were named to serve as informal national coordinators for each project area. These recommendations are included in this book together with the names of the national coordinators. It is hoped that these activities will encourage active communication and collaboration among scientists working with forage legumes.

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Summary of Recommendations for Collaborative Research Projects Among Scientists From Australia, New Zealand, and the United States

At a final session of the workshop, one delegate from each country summarized the views of each country's participants on priority research needs and opportunities for future cooperation. From these ideas, the participants synthesized eight high-priority research areas as listed below, but not in order of importance. To encourage active collaboration among scientists in Australia, New Zealand, and the United States, several scientists were asked to serve as national coordinators for each of these research areas.

1. Legume Persistence Under Grazing

A serious limitation to greater use of legumes for animal production is the lack of persistence in temperate, Mediterranean, and tropical pastures. Priority should be given to research that defines the mechanisms involved in the interactive effects on plant persistence of defoliation, grazing management, edaphic stresses, pests, and diseases.

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2. Nitrogen Relationships

A major role of forage legumes in animal production is to fix atmospheric nitrogen, which is used to increase the quantity and quality of forage fed to ruminants or for nitrogen nutrition of subsequent crops in rotational systems. Attention was drawn to the paucity of information on the actual quantity of nitrogen fixed, nitrogen transformations, and the fate of this nitrogen in different farming systems. Priority should be given to research designed to measure and model nitrogen turnover and balances in diverse forage-livestock systems and environments, with special reference to comparing legume and fertilizer sources of nitrogen.

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3. Mechanisms of Rhizobial Nodulation

Nodulation with an effective strain of *Rhizobia* is necessary to enable a legume to fix atmospheric nitrogen. The introduction of more efficient rhizobial strains offers one prospect for increasing symbiotic fixation by forage legumes. Priority should be given to research on the mechanisms involved in successful nodulation, particularly competition for nodulation sites as influenced by rhizobial strain/legume host/edaphic factor interactions.

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4. Efficiency of Protein and Energy Utilization by Ruminants

Attention was drawn to differences between legumes and grasses, and among legume species, in the efficiency with which their protein and energy are used by ruminants. Discussion centered on the possible cause of these differences and ways that forages might be altered to overcome some of the limitations. Priority should be given to determining the factors controlling the efficiency of protein and energy utilization by ruminants on forage diets.

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5. Categorizing Legume Germplasm to Minimize Edaphic Limitations

Legumes have been successful in many farming systems, but few vigorous, adapted legumes are used in large areas of temperate, Mediterranean, and tropical zones. Priority should be given to the collection, description, and development of forage legumes to minimize edaphic limitations of moisture, soil pH, and nutrients, with special emphasis on annuals and lucerne.

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6. Shrub and Browse Legumes

The success of Leucaena in tropical areas has drawn attention to the valuable contribution that shrub and browse legumes can make to animal production. Other shrub and browse legumes should be sought and developed for both tropical and temperate regions.

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7. Breeding of Forage Legumes, Including Genetic Engineering

Legume breeding has been successful as a method for enhancing the production and nutritional value of legumes for animal production. Priority should be given to conventional plant breeding, enhanced where appropriate by genetic engineering. This work is needed for reducing bloat potential, for improving protein metabolism by the animal, and for increasing nitrogen fixation through more efficient legume plants and rhizobia.

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8. Nutritional Value

The superior nutritional value of legumes, compared with grasses, is probably associated with the more favorable physical and chemical composition of legume cell walls. Priority should be given to studies of the cell walls of legumes and grasses to determine physical, histological, and biochemical differences and their effects on nutrient availability and resistance of the indigestible fraction to breakdown.

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Contents

USE OF FORAGE LEGUMES

The Distribution and Use of Forage Legumes in Australia

K.R. Helyar[1]

Abstract

The Australian continent is divided into 23 bioclimatic zones based on the plant growth potential in an area and its distribution through the year. The zones vary from non-seasonal humid tropical areas, to the seasonal and arid tropical zones, and seasonal and non-seasonal temperate regions. Within each zone the major and minor legume species used for pasture improvement are listed. Pasture productivity data are presented including typical dry matter yield and botanical composition values for grazed pastures. The levels of wool production and steer liveweight gains measured in about 60 grazing experiments illustrate the range of animal productivity on improved legume-based pastures across the continent. Broad relationships between animal production and pasture growth and seasonality are shown to exist. These relationships demonstrate the lower levels of animal production achieved using tropical or megatherm compared with temperate or mesotherm species, in environments with equivalent pasture growth potentials.

Introduction

Forage legumes are used in Australia for two main purposes. Firstly to provide a high quality component of the diet of grazing animals, and secondly to supply nitrogen to the grazing ecosystem via the fixation of atmospheric nitrogen. Throughout the country pastures are grazed the year-round, and with the exception of the dairy industry, conserved forage is predominantly used to buffer feed supplies between years (i.e., for drought feeding), rather than to redistribute feed within a year (Willoughby 1970). Small areas of irrigated lucerne (alfalfa) are grown for hay production, and limited areas of annual legumes such as cowpeas, lupins, lab-lab, and vetches are grown as crops for grazing or conservation.

Understanding the distribution and use of the various pasture legume species from the temperate southern latitudes to the tropical north requires an understanding of the Australian climate.

Bioclimatic Classification of Australia

The climate varies widely from the tip of Cape York (10°S) to southern Tasmania (44°S). I have used a bioclimatic classification of Australia (Nix 1982) as a basis for discussing the distribution and use of forage legumes (fig. 1). This numerical classification is based on a calculated plant growth potential for the area, and its distribution through the year. These factors (total pasture production and its seasonal pattern) also dominantly determine the potential for beef production from pastures in northern Australia (McCown et al. 1981) and sheep and cattle production in southern Australia (Allden 1982).

Zones 1 to 8 (fig. 1) are areas in which legume species with high temperature requirements for growth are adapted. These are the megatherm or tropical species with maximum photosynthetic rates between 26° and 28°C. Zones 12 to 23 are areas suited to mesotherm (temperate) legumes with optimum photosynthetic rates between 19° and 22°C. Zones 8 to 11 are areas of overlap between the mesotherm and megatherm groups. Examination of the moisture and growth indices (Nix 1982) for indicator locations in the different zones (table 1) shows they are numbered roughly in order of increasing aridity within the species temperature classes. Each of the indices in table 1 varies between 0 (complete limitation to plant growth) and 1.0 (no limitation to plant growth). The growth index includes effects of temperature, light, and moisture on the growth potential, and assumes an available soil moisture store of 100 mm.

Forage Legume Species

The species and cultivars of forage legumes sown or naturalized in the different zones are listed below. Species followed by D in parenthesis are the dominant sown legumes, while those followed by M are of minor importance commercially. The main references used in preparation of these lists were Moore (1970), Weston et al. (1981), Humphreys (1980), O'Reilly (1975), and the journal papers used in preparation of table 2 and figures 4 to 7. The potential distribution of the main megatherm and mesotherm pasture legumes is also shown in figure 2.

Megatherm Zones

Zone 1--Non-seasonal, humid, megatherm:
- Wet coastal lowlands--Centro (*Centrosema pubescens*); Common (D) and cv. Belalto (M); *Stylosanthes guianensis* var. *guianensis*; cv. Schofield, Cook.
- Adjacent highlands--*Desmodium uncinatum*; cv. Silverleaf (M); *Neonotonia wightii*; cv. Tinaroo, Malawi (D); *Trifolium semipilosum*; cv. Kenya (M); *Desmodium intortum*; cv. Greenleaf (D).
- All areas--*Leucaena leucocephala*; cv. Peru, Cunningham (M).

Zone 2--Slightly seasonal, humid, megatherm:
- As for zone 1 except for dominance of *S. guianensis* var. *guianensis* cultivars over centro.

Zone 3--Slightly seasonal, humid, megatherm/mesotherm:
- All areas--*Macroptilium atropurpureum*; cv. Siratro (D); *Leucaena leucocephala*; cv. Peru, Cunningham (M).
- Northern section--*S. guianensis* var. *guianensis*; cv. Graham (M).
- Southern section--*Desmodium intortum*; cv. Greenleaf (M); *Neonotonia wightii*; cv. Tinaroo, Cooper (M).
- Highlands--*Trifolium semipilosum*; cv. Safari (M); *T. repens*; cv. Naturalized, Haifa (D).

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Figure 1--A bioclimatic classification of Australia, based on Nix (1982) and Laut et al. (1980). The numerals identify the zone numbers referred to in the text, and the sites are the locations of stocking rate experiments also identified on figures 3, 4, and 6.

Table 1 - Moisture index and growth index data for selected locations in the bioclimatic zones marked in figure 1

Zone	Site	Wkly moisture index Max	Wkly moisture index Min	CVMI	Weeks MI <0.25	Growth Indices* Su	Growth Indices* Au	Growth Indices* Wi	Growth Indices* Sp
Megatherm zones									
1	Innisfail (I)	1.0	0.82	6.2	0	0.88	0.74	0.47	0.67
2	Iron Range (IR)	1.0	.08	54.4	13	.86	.83	.48	.17
3	Mackay (Mc)	1.0	.21	40.3	4	.83	.65	.18	.24
	Gympie (Gy)	.92	.36	28.7	0	.71	.45	.04	.28
4	Theodore (Th)	.58	.15	27.7	6	.46	.20	.03	.23
	Emerald (E)	.47	.12	37.4	22	.35	.16	.03	.17
5	Moreton (Mo)	1.0	.03	81.8	22	.86	.77	.06	.15
	Katherine (Ka)	1.0	.03	102	29	.84	.41	.03	.17
	Mt. Surprise (Mt. S)	.96	.04	97.8	33	.67	.27	.04	.12
6	Derby (Db)	.85	.03	112	35	.58	.25	.04	.05
	Daly Waters (DW)	.70	.03	98.7	31	.51	.20	.03	.12
	Croydom (Cr)	.89	.04	109	33	.65	.25	.04	.10
7	Wittenoom (W)	.38	.03	68.1	36	.19	.14	.06	.04
	Alice Springs (AS)	.19	.06	37.5	52	.17	.05	.002	.08
	Longreach (Lg)	.34	.06	45.1	39	.25	.12	.02	.11
Megatherm/mesotherm zones									
8	Beerwah (B)	1.0	0.61	16.5	0	0.78	0.59	0.13	0.41Mg**
						.70	.80	.77	.62Ms
	Grafton (G)	.86	.36	27.7	0	.50	.35	.04	.25Mg
						.40	.56	.52	.35Ms
9	Kempsey (Ke)	1.0	.47	23.5	0	.56	.74	.63	.61Ms
	Sydney (S)	1.0	.35	33.4	0	.47	.69	.59	.56Ms
10	Goondiwindi (Goo)	.62	.19	38.9	13	.27	.11	.01	.15Mg
						.16	.22	.29	.21Ms
11	St. George (StG)	.51	.12	42.7	38	.22	.10	.01	.12Mg
						.09	.18	.22	.14Ms
Mesotherm Zones									
12	Werribee (We)	0.92	0.17	50.7	8	0.22	.028	0.15	0.40
	Bothwell (Bo)	1.0	.20	47.4	5	.22	.14	.01	.24

Table 1 - Moisture index and growth index data for selected locations in the bioclimatic zones marked in figure 1--Continued

Zone	Site	Wkly moisture index Max	Min	CVMI	Weeks MI <0.25	Growth Indices* Su	Au	Wi	Sp
13	Glen Innes (GI)	.99	.41	29.1	0	.51	.31	.06	.47
14	Oberon (O)	1.0	.42	31.7	0	.41	.23	.01	.36
15	Tumbarumba (Tu)	1.0	.27	41.0	0	.30	.25	.02	.52
17	Mt. Barker (Mt.B)	1.0	.14	59.8	16	.15	.35	.27	.56
	Pandana (K.I.)	1.0	.09	65.5	19	.12	.31	.26	.45
18	Armidale (A)	.85	.37	29.4	0	.42	.26	.05	.33
	Tamworth (Tam)	.83	.30	41.7	0	.26	.27	.29	.33
19	Rutherglen (Ru)	1.0	.17	57.6	13	.20	.24	.09	.48
	Canberra (Ca)	.89	.23	46.0	4	.25	.22	.04	.29
20	Moree (M)	.72	.21	49.9	12	.16	.25	.31	.21
	Temora (Te)	.85	.14	58.8	17	.17	.22	.09	.26
21	Kojonup (Koj)	1.0	.07	77.5	22	.08	.24	.24	.39
	Meredin (Me)	.82	.08	89.8	31	.06	.17	.27	.15
	Walpeup (Wal)	.63	.10	69.1	30	.11	.13	.15	.19
22	Condobolin (Co)	.69	.18	55.4	24	.14	.22	.17	.22
	Deniliquin (De)	.80	.12	71.4	27	.13	.18	.19	.22
23	Cunnamulla (Cu)	.40	.09	49.0	41	.05	.13	.17	.09
	Broken Hill (BH)	.25	.07	38.7	48	.08	.11	.07	.11
	Norseman (Nor)	.52	.09	66.6	30	.10	.16	.20	.12

*For megatherm legumes in megatherm zones, for mesotherm legumes in mesotherm zones and for both in the megatherm/mesotherm zones.

**Mesotherm (Ms) or megatherm (Mg) growth indices.

MI = moisture index; CVMI = coefficient of variation of the weekly mean moisture indices.

Zone 4--seasonal, sub-humid, megatherm:
Northern and eastern section--Stylosanthes hamata; cv. Verano (D); S. humilis; naturalized (M); S. scabra; cv. Seca and Fitzroy; and S. guianensis var. intermedia, cv. Oxley (M).
Southern and eastern section--Macroptilium atropurpureum; cv. Siratro (D); Medicago sativa; various cultivars (M); Medicago truncatula; var. truncatula; cv. Jemalong and Cyprus (M); Stylosanthes scabra; cv. Fitzroy (western section) (M); and S. guianensis var. intermedia, cv. Oxley (D).
Western section--no suitable legumes (see fig. 2).

Zone 5--Highly seasonal, sub-humid, megatherm:
High rainfall section (>1,200 mm annually--Stylosanthes guianensis var. guianensis, cv. Graham, Cook and Endeavour (D); S. hamata; cv. Verano (M).
Medium and low rainfall section (<800 and 800-1,200 mm areas)--S. hamata; cv. Verano (D); S. humilis, naturalized and cv. Lawson, Gordon, Peterson (M); S. scabra; cv. Seca and Fitzroy (M).

Zone 6--Highly seasonal, semi-arid, megatherm:
As for the medium and low rainfall sections of zone 5 but with S. scabra cultivars likely to be more important in drier areas.

Zone 7--Arid, megatherm:
This zone is too dry for the establishment of sown pastures.

Megatherm/Mesotherm Overlap Zones

Zone 8--Slightly seasonal, humid, mesotherm/megatherm:
Trifolium repens; cv. Haifa and Naturalized (D); Macroptilium atropurpureum cv. Siratro (M); Neonotonia wightii; cv. Tinaroo, Cooper, Clarence, (M); Desmodium uncinatum; cv. Silverleaf (M); D. intortum; cv. Greenleaf (M); Trifolium semipilosum, var. glabrescens, cv. Safari (M); Lablab purpureus; cv. Rongai, Highworth (M); Medicago sativa; cv. (various) (M); Leucaena leucocephala, cv. Peru, Cunningham (M); Vicia sativa; cv. Golden Tares (M); Aeschynomene falcata; cv. Bargoo (M) (drier areas); Lotononis bainesii; cv. Miles (M).

Zone 9--Slightly seasonal, humid, mesotherm (megatherm grasses):
Trifolium repens, cv. Siral, Haifa, Grasslands Huia, Irrigation, Ladino (D); Medicago sativa, cv. (various) (M); Trifolium pratense, cv. Redwest, Redquin, Grasslands Humua, Grasslands Turoa (M); Vigna sinensis, cv. (various) (M); Vicia sativa, cv. Golden Tares (M).

Zone 10--Slightly seasonal, sub-humid, mesotherm (megatherm grasses):
Medicago sativa, cv. (various) (D); Medicago truncatula, var. truncatula, cv. Jemalong, Cyprus (D); Vicia villosa, ssp. dasycarpa, cv. Namoi (M); Medicago scutellata, cv. Robinson, Sair, Sava (M); Naturalised medics--M. hispida, M. minima, M. polymorpha (M).

Zone 11--Slightly seasonal, semi-arid, mesotherm (megatherm grasses):
Medicago truncatula, var. truncatula, cv. Jemalong, Cyprus (D); Naturalized medics as for zone 10.

Mesotherm Zones

Zone 12--Moderately seasonal, humid, mesotherm:
Trifolium repens, cv. Grasslands Huia, Ladino, Louisiana Sl. Haifa, Siral and naturalised (D). T. pratense, cv. Redwest, Redquin (M); Trifolium subterraneum ssp. subterraneum cv. Mt. Barker, Woogenellup, Tallarook, Clare (D); Medicago sativa, various cultivars (M).

Zone 13--Slightly seasonal, humid, mesotherm:
Trifolium repens, cv. Haifa, Grasslands Huia, Ladino, Naturalized (D), T. pratense, cv. Redwest, Redquin (M); Trifolium subterraneum ssp. subterraneum cv. Mt. Barker, Woogenellup (D); Medicago sativa, various cultivars (M).

Zone 14--Moderately seasonal, humid, mesotherm:
As for zone 13.

Zone 15--Slightly seasonal, humid, mesotherm/microtherm:
As for zone 12.

Zone 16--Non-seasonal, humid, microtherm:
There are no significant pasture areas in this microtherm or cold temperate zone. Microtherm species have optimum temperatures for photosynthesis between 10° and 14°C (Nix 1982).

Zone 17--Seasonal, sub-humid, mesotherm:
Trifolium subterraneum ssp. subterraneum cv. Woogenellup, Mt. Barker, Bacchus Marsh (D); Lupinus luteus, cv. Weiko III (M); Medicago sativa, various cultivars (M); Medicago truncatula, var. truncatula, cv. Cyprus, Jemalong (alkaline soils) (M); Trifolium repens, cv. Haifa and naturalised.

Zone 18--Slightly seasonal, humid/sub-humid, mesotherm:
Trifolium subterraneum ssp. subterraneum, cv. Woogenellup, Mt. Barker (D); Trifolium repens, cv. Haifa and naturalised (M); Medicago sativa, various cultivars (M).

Zone 19--Moderately seasonal, humid/sub-humid, mesotherm:
Trifolium subterraneum ssp. subterraneum, cv. Mt. Barker, Woogenellup, Bacchus Marsh, Seaton Park (D); Trifolium repens, cv. Siral, Haifa (M), Medicago sativa, various cultivars (M).

Zone 20--Moderately seasonal, sub-humid, mesotherm:
Trifolium subterraneum ssp. subterraneum, cv. Woogenellup, Mt. Barker (D, southern section); Medicago sativa, various cultivars, (D, northern section); Medicago truncatula var. truncatula, cv. Cyprus, Jemalong (M); Vicia villosa ssp. dasycarpa, cv. Namoi (M); various Medicago ssp. naturalised on alkaline soils.

Zone 21--Highly seasonal, sub-humid/semi-arid, mesotherm:
Trifolium subterraneum ssp. subterraneum, cv. various early maturity cultivars (D); Medicago truncatula var. truncatula, cv. Cyprus, Jemalong, Hannaford, Ghar (D); Medicago littoralis, cv. Harbinger (M); Trifolium hirtum, cv. Kondinin, Olympus, Sirint (M); naturalized annual Medicago and Trifolium species.

Zone 22--Moderately seasonal, semi-arid, mesotherm:
As for Zone 21 without M. littoralis and T. hirtum and plus Medicago sativa (various cultivars) (M).

Zone 23--Moderately to highly seasonal, arid, mesotherm:
This zone is too dry for the establishment of sown pastures.

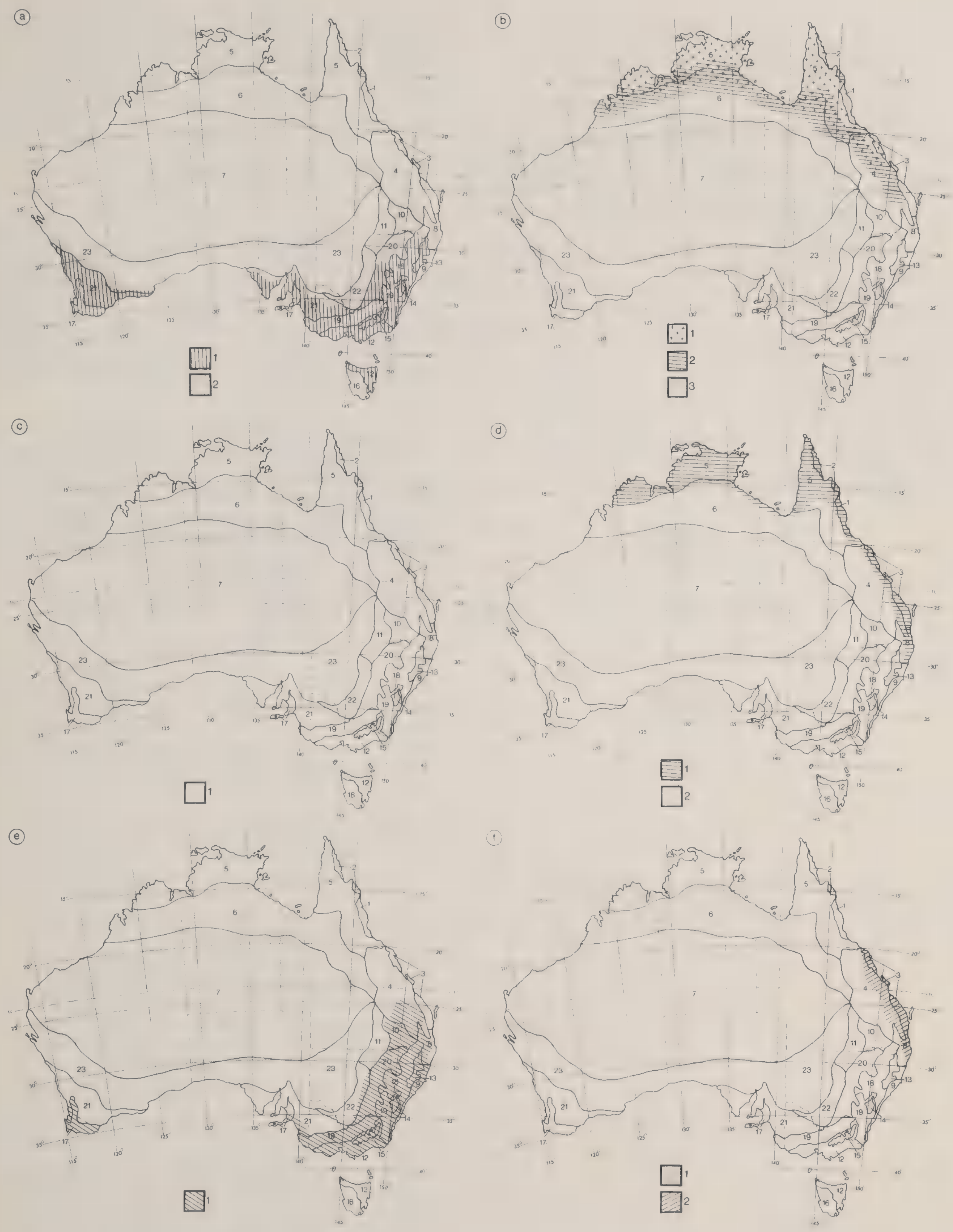


Figure 2--Potential distribution of the major pasture legume species under non-irrigated conditions. Parenthesis numbers refer to shading identification on the map key. (a) Subterranean clover (*Trifolium subterraneum*) (1), barrel medic (*Medicago tribuloides*) and other annual medics (2); (b) Townsville stylo (*Stylosanthes humilis*) (1), Caribbean stylo (*S. hamata*) (1), shrubby stylo (*S. scabra*) (2) and centro (*Centrosema pubescens*) (3); (c) White clover (*Trifolium repens*) (1) and Red clover (*T. pratense*) (1); (d) Leucaena (*Leucaena leucocephala*) (1), Stylo (*Stylosanthes guianensis* var. *guianensis*) (2); (e) Lucerne (*Medicago sativa*) (1); (f) Desmodium (*Desmodium uncinatium* and *D. intortum*) (1), glycine (*Neonotonia wightii*) (1), Kenya white clover (*Trifolium semipilosum*) (1), Siratro (*Macroptilium atropurpureum*) (2) and fine stem stylo (*Stylosanthes guianensis* var. *intermedia*) (2).

Pasture Production

The quantity of pasture produced and its seasonal pattern of production are determined by limitations imposed by moisture, temperature, light, mineral nutrient availability, plant population, and the phenological development patterns of the species present. For legume-based pastures, the percentage legume in the sward and the effectiveness of the nitrogen fixation process are also important.

Seasonal Patterns of Pasture Growth

Growth indices calculated according to Nix (1982) for pasture legumes show the potential pasture growth patterns in various areas for legumes adequately fertilized with nutrients other than nitrogen (fig. 3). For this potential to be achieved, species with phenological development patterns (e.g., maturity types) matching the environment must be sown and nitrogen fixation conditions need to be optimum. Given these conditions, pasture growth in the megatherm areas is dominantly controlled by moisture, being maximum in summer and minimum in winter/spring (fig. 3a).

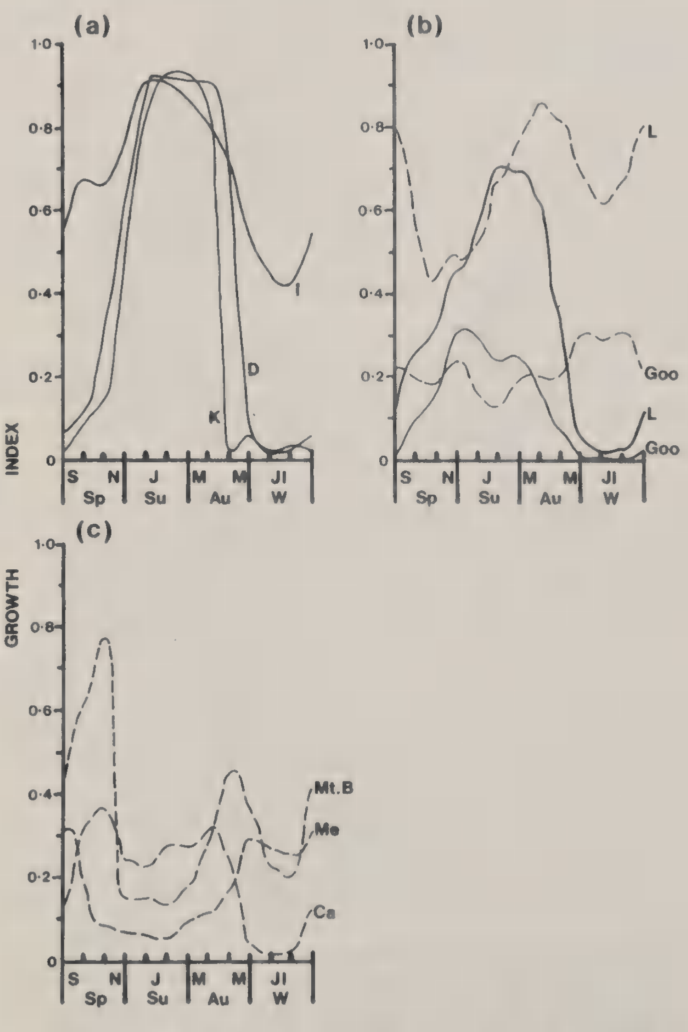


Figure 3--Growth index curves for pasture legume species in different locations in Australia. (I is Innisfail in zone 1; D and K are Darwin and Katherine in zone 5; L and Goo are Lismore and Goondiwindi in zones 8 and 10; Mt. B, Me and Ca are Mount Barker, Meredin and Canberra in zones 17, 21 and 19.

The length and severity of the winter/spring dry season increases from short and mild in zone 1 (growth index just below 0.5 for 3 months at Innisfail) to long and severe in zone 7 (growth index below 0.1 for 5 months at Katherine) (fig. 3a).

In the south the growth index pattern for mesotherm species is bimodal, with a small autumn and usually a larger spring peak (fig. 3c). The winter trough is caused by low temperatures and the summer trough by low soil moisture levels. The winter trough is more severe in the cooler eastern highlands (Canberra), and the summer trough is longer and more severe as rainfall decreases (compare Meredin and Mt. Barker, fig. 3c).

The megatherm/mesotherm zones have pasture growth patterns intermediate between the mesotherm and megatherm patterns. These result from the northerly trend toward higher summer rainfall, greater winter temperatures, and lower winter/spring rainfall (table 1). In this area, growth patterns for megatherm legumes are strongly temperature dependent, but mesotherm legumes are not strongly seasonal in growth (fig 3b).

Pasture Yield and Composition

Levels of dry matter production by improved pastures are given in table 2. Wherever possible, these values have been taken from experiments with grazed pastures, that were conducted over a period greater than two years, and were adequately fertilized with nutrients other than nitrogen.

In both megatherm and mesotherm areas, commercially viable pasture improvement (synonymous with sowing introduced legumes and applying fertilizers to overcome nutrient deficiencies) has occurred in areas where the mean annual productivity exceeds 2-3 t dry matter per hectare (e.g., drier sites in zones 5 and 21, and zone 22, table 2). The mean productivity of legume-based pastures in the mesotherm zones increases to 12 to 15 t ha^{-1} yr^{-1} in the climatically favoured areas (e.g., zones 12 to 15, table 2). In the megatherm and megatherm/mesotherm zones, mean yields in the most favoured areas (zones 1 and 8) are seldom greater than 10-12 t ha^{-1} yr^{-1}. This probably reflects the lower average legume content, and hence nitrogen fixation levels, achieved by legumes in competition with the megatherm grasses compared with mesotherm grasses (15%-30% compared with 20%-60% for zones 1 and 8 versus 12-15 respectively, table 2). In contrast, yields of 20-30 t ha^{-1} yr^{-1} have been recorded for nitrogen fertilized grass in the favourable megatherm zones (table 2), whilst pasture yields with and without nitrogen are often similar in the favourable mesotherm zones (e.g., zone 18, table 2). The higher pasture legume content achieved in the mesotherm zones probably leads to sufficient nitrogen fixation for near maximum growth response of the legume/grass pasture within the light, temperature, and moisture limitations of the environment.

Table 2 - Yield data from improved legume-based pastures, adequately fertilized with nutrients other than nitrogen, and from nitrogen-fertilized pastures, in different bioclimatic zones; most of the data were collected over 2 to 5 years

Bioclimatic zone	Site	Dominant species	Percentage legume (%) or nitrogen rate (kg/ha/yr)	Dry matter yield range and (mean) (t/ha/yr)	Measurement technique[1] and reference[2]
Megatherm					
1	South Johnstone/	Guinea grass/Centro	5%-15%	7-12	PY, 36
	Utchee Ck.	Signal & pangola grasses	196 N	16-27	CY, 36
3	Koumala	Setaria/Siratro, *S. guyanensis*	Mostly <10%	2.2-13(7.0)	PY, 71
		Setaria	300 N	2.8-13(5.9)	PY, 71
4	Narayan	Green panic, Buffel grass, Rhodes grass Siratro	15%-20%	3.6-8.8	CY, 54
	Rodd's Bay	Speargrass/Siratro, Townsville stylo	10%-30%	3-10	PY, 38
		Green panic, *P. plicat.*, Rhodes grass	336 N	5-13	PY, 38
5	Heathlands	Siratro, *S. guyanensis*		5.3-9	UY, 12
	Wrotham Pk.	Native grass/Verano or Townsville stylo	Up to 50%	3-5	PY, 34
	Lansdown	Townsville stylo	Up to 50%	1.3-6	PY, 32
	Swans Lagoon	Townsville stylo	11%-91%	0.4-7	PY, 74
	Kangaroo Hills	Native grass/ Verano stylo	Up to 50%	3-6	PY, 34
	Katherine	Native grass/ Townsville stylo	30%-80%	3-5	CY, 61
Megatherm/mesotherm zones					
8	Wollongbar	Kikuyu/white clover	5%-20%	8-11	CY, 57
		Kikuyu	336 N	17-27	CY, 57
		Kikuyu	1,000 N	30	UY, 21
	Samford	Setaria/Siratro	20%-30%	5-8.5	PY, 48
		Paspalum/Kenya white clover	10%-20%	5-6	UY, 45
10	Goondiwindi	Buffel grass, Green panic		0.5-2.2	PY, 17
Mesotherm zones					
12	Hamilton	Perennial ryegrass, phalaris/subterranean clover		8-15(11.5)	CY, 6

Table 2 - Yield data from improved legume-based pastures, adequately fertilized with nutrients other than nitrogen, and from nitrogen-fertilized pastures, in different bioclimatic zones; most of the data were collected over 2 to 5 years--Continued

Bioclimatic zone	Site	Dominant species	Percentage legume (%) or nitrogen rate (kg/ha/yr)	Dry matter yield range and (mean) (t/ha/yr)	Measurement technique[1] and reference[2]
	Ellinbank	Perennial ryegrass/ white & subterranean clovers		(12.8)	CY, 29
15	Tumbarumba	Phalaris, perennial ryegrass/subterranean clover	16%-35%	13-16(14.5)	CY, 23 24
17	Kangaroo Island	Annual grasses/subterranean clover	20%-80%	6.5-11.3(9.2)	CY, 16
	Kojonup	Annual grasses/subterranean clover	38%-84%	5.0-6.0	CY, 35
		Annual grasses	176 N	7.0-8.0	CY, 35
18	Armidale, Chiswick, and Glen Innes	Phalaris, fescue/ subterranean clover		4.4-14.4(9.9)	MODEL, 67
		Native grasses/subterranean and white clovers	2%-30%		63, 64
		Phalaris/white and subterranean clovers		9.4-12.8(11.1)	CY, 3
		Phalaris, perennial ryegrass	135 N	8-10	UY, 22
		Tall fescue, phalaris	276 N	5-7(5.9)	CY, 41
19	Canberra	Phalaris or volunteer grass/subterranean clover		6.8	UY, 69
		Same		7.2	UY, 51
		Same		6.3	UY, 52
	Wagga	Same	8%-74%	3.5-8.0(6.1)	PY, 50
	Kybybolite	Wimmera ryegrass, barley grass/ subterreanean clover		8-12(10.4)	CY, 9
20	Tamworth	Lucerne	90%-100%	4.0-7.5	CY,70
	Cowra	Annual grasses/ lucerne, subterranean clover.	10%-25%	3.3-11.0	CY, 44
22	Condobolin	Lucerne	90%-100%	0.8-3.5(2.0)	CY, 11

[1]Measurement technique codes: PY = peak yield on offer at low stocking rates; CY = periodic harvests from areas excluded from grazing for the regrowth period; UY = periodic harvests from ungrazed plots.
[2]Reference numbers refer to the numbered reference list.

There is also some indication in the table 2 data that average legume contents are less in association with perennial grasses in long growing season areas, than with annual grasses in short growing season zones (contrast zones 15 and 18 with zones 17 and 19, and zones 1 and 3 with zone 5, table 2). There is evidence that the optimal nitrogen economy of a grazed pasture is achieved at about 30% legume in the sward (Tothill 1978). Legume contents below this value are a major cause of reduced productivity, because of lowered N inputs with resultant lowered yields and lowered pasture quality (e.g., Robinson 1977, Evans 1970).

Animal Production

The stocking rates and animal production levels on legume-based, non-irrigated pastures in Australia are related to the quantity and quality of the pasture produced and to the seasonal pattern of production. There are large differences in seasonal pasture growth patterns across the continent (fig. 3). Parallel variations occur in feed quality between growing, mature green, and dry feed periods. The effects of the feed supply on production from grazing animals is illustrated on figures 4 to 7.

In the mesotherm and mesotherm/megatherm areas, stocking rate and wool production data from 30 grazing experiments has been summarised within each bioclimatic zone (fig. 4), and as a function of the growth index times a green index (fig. 5). The green index (0-1) indicates the proportion of the year green feed is available, and is equated with the proportion of the year the moisture index is greater than 0.10 for megatherm species (cf. McCown et al. 1981) or the proportion of the summer 26 weeks the growth index is greater than 0.2 for mesotherm species (this assumes pastures are green in winter). Similarly, the results of 34 grazing experiments in which annual liveweight gains of steers (mostly 200-300 kg liveweight at the start of a year) were measured, are shown for the bioclimatic zones (fig. 6), and as a function of the growth index times the green index (fig. 7). These experiments were dominantly in the megatherm

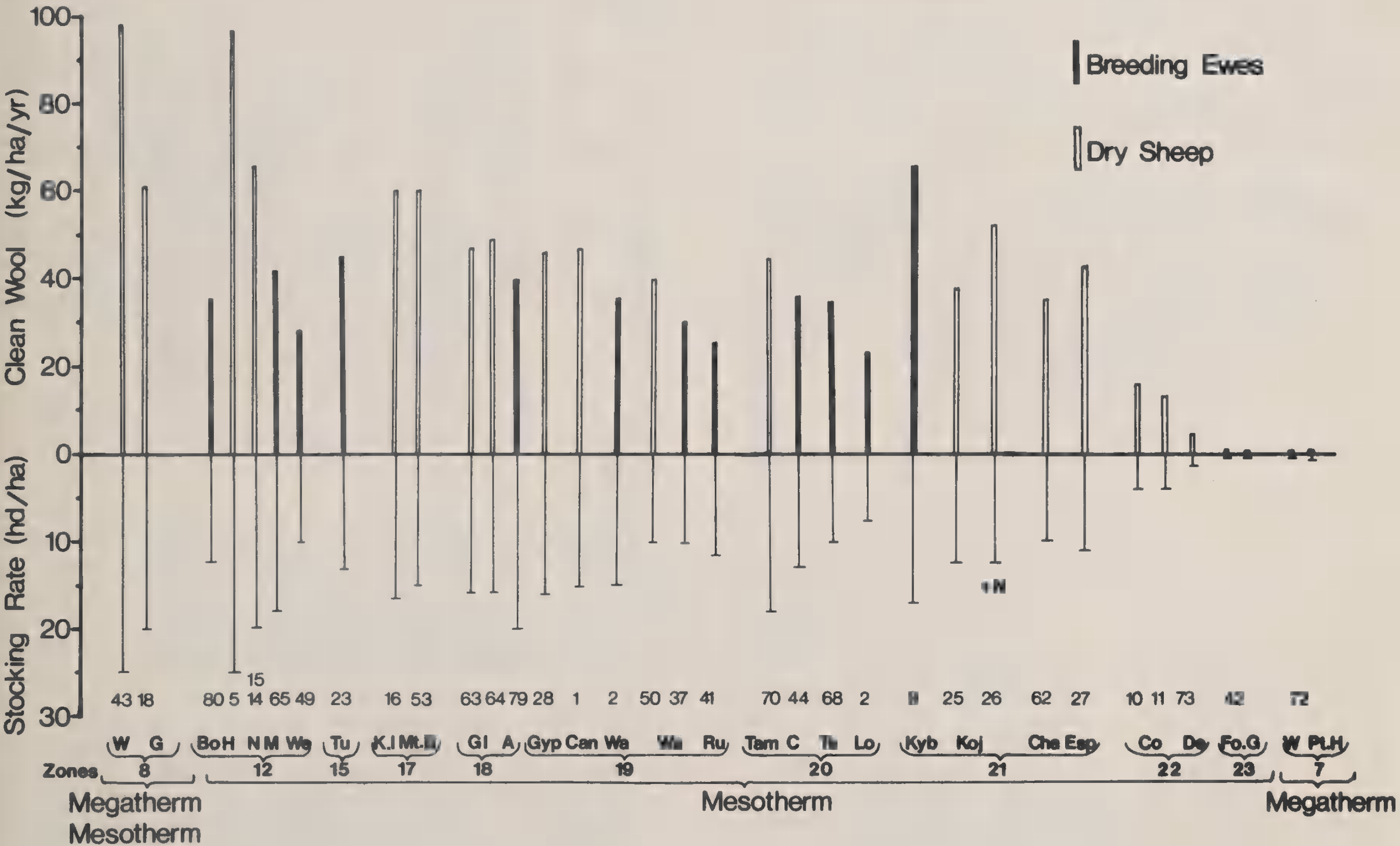


Figure 4--Clean wool production at the highest stocking rates compatible with stable pasture composition, in various bioclimatic zones in southern Australia. The numbers refer to publications listed in the bibliography. The location abbreviations also appear on figure 1. All experiments to the right of Te in zone 20 are with merino sheep. Other breeds, merinos and merino crossbreds were included in the data to the left of Te.

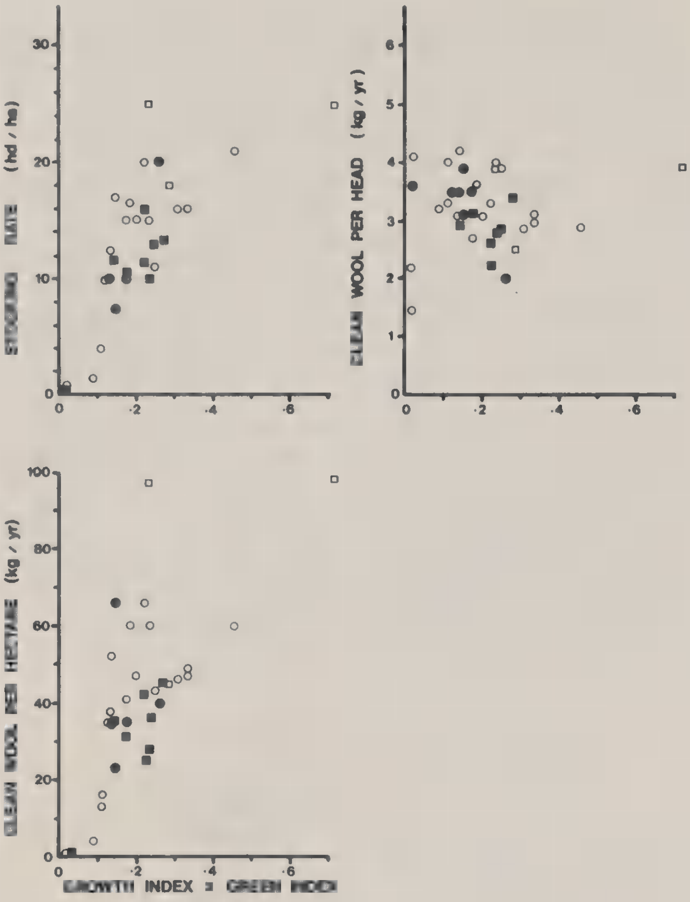
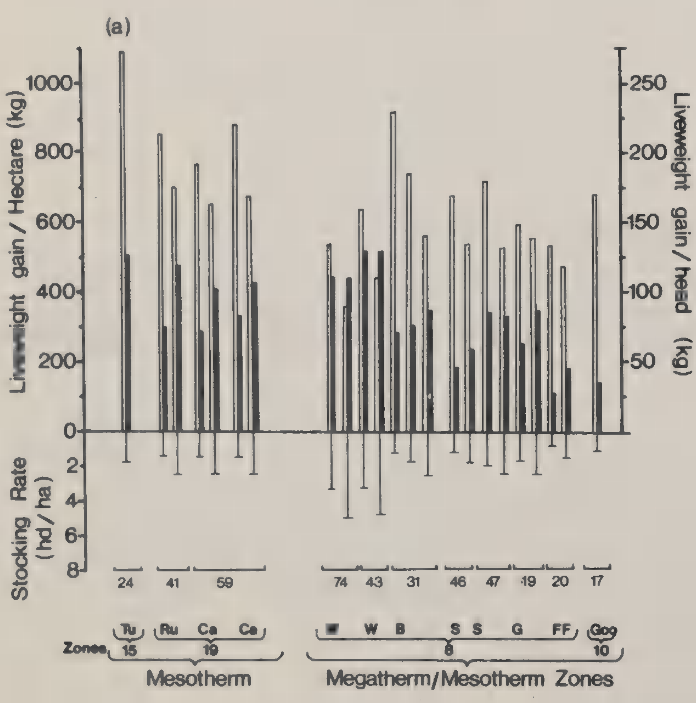
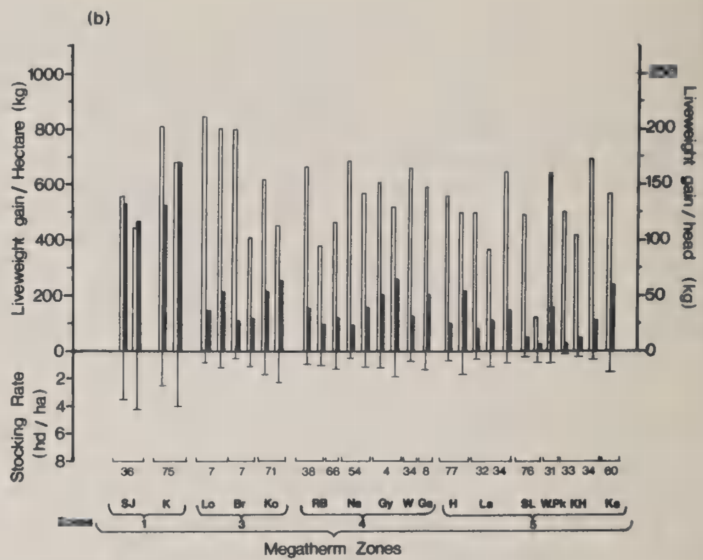


Figure 5--The data from figure 4 for stocking rate, clean wool production per head, and per hectare, plotted against the growth index for mesotherm legumes times the proportion of the year green feed is available. Breeding status is indicated by solid (wet) or open (dry) symbols. The circles represent Merino sheep and the squares Merino crossbreds or other breeds.





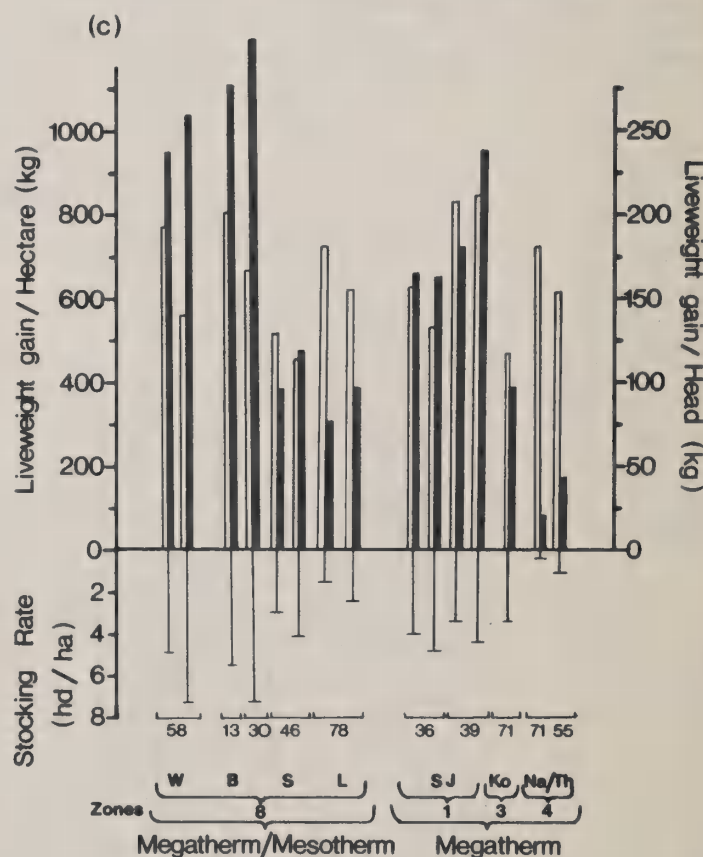


Figure 6--Steer or heifer liveweight gains per hectare (solid columns) and per head (open columns), and stocking rates, from grazing experiments with legume-based (a and b) and nitrogen-fertilized grass pastures (c), in various zones in Australia. The numbers refer to publications listed in the bibliography. The location abbreviations also appear on figure 1.

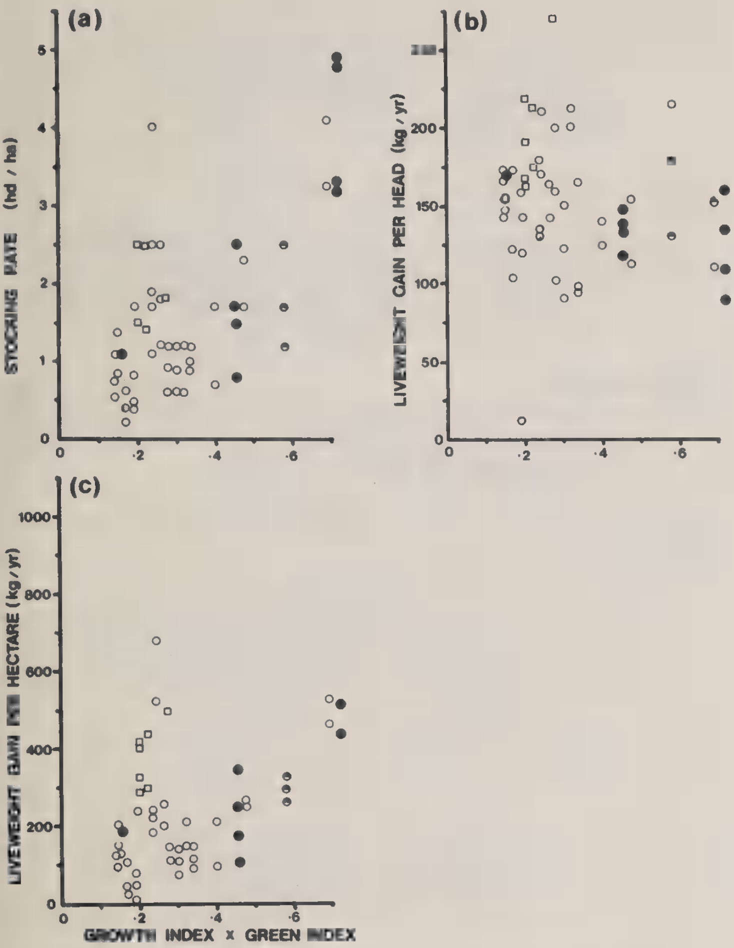


Figure 7.--The data from figure 6 for stocking rate, liveweight gains per head, and per hectare, plotted against the pasture legume growth index times the proportion of the year green feed are available. The symbols identify the type of pasture species: open circle, megatherm grass and legume; filled circle, megatherm grass/mesotherm legume; half-filled circle, megatherm grass/both legumes; square, mesotherm grass and legume.

zones but extend into mesotherm areas. Wherever possible two stocking rates were plotted, the higher rate being the highest experimental rate below the stocking rate for maximum liveweight gain per hectare. For both the sheep and cattle experiments two or more years data have been meaned.

The carrying capacity in the various mesotherm zones varies from 0.1 to 25 sheep/ha (figs. 4 and 5). Levels of wool production per head are greater in areas with the longest growing seasons (zones 8 and 12-15), are similar for many mesotherm zones, and are lower in areas with very long dry feed seasons (e.g., zone 7). Thus across a wide range of climates, reductions in stocking rate roughly compensate for reduction in dry matter production (fig. 5).

The growth index x green index plots (fig. 5) show the stocking rates and wool production per hectare are lower for breeding than non-breeding sheep in given growth and seasonality environments. Furthermore stocking rates and production rise more sharply in response to the index for mesotherm than for the mesotherm/megatherm areas (fig. 5). The divergence of the stocking rate and wool production per hectare trends can be attributed to the lower quality of the megatherm C_4 grasses compared with mesotherm C_3 grasses (Norton 1982) and restricted growth and nitrogen fixation by the mesotherm legumes in association with strong megatherm grass competition. Insect competition may also be involved (Braithwaite et al. 1958).

Beef production from unirrigated improved legume-based pastures varies from 25-50 kg liveweight gain/ha/yr in marginal megatherm areas, to 500-600 kg/ha/yr in the better mesotherm and megatherm environments (fig. 6a and 6b). Liveweight gains per head range from 250 to 300 kg/yr in the most favourable mesotherm environments, while values greater than 200 are rare in megatherm and megatherm/mesotherm areas (fig. 6a and 6b). In the better megatherm environments (zones 1 to 4), liveweight gains of 150 to 180 kg/hd/yr are usually associated with economic optimum stocking rates. In zone 5, optimum liveweight gain rates are usually less than 150 kg/hd/yr.

Stocking rates on improved pastures vary from 0.2-0.5 hd/ha in the drier areas of zones 4 and 5 (e.g., Kangaroo Hills, Westmead) to 3-5 hd/ha in zones 1 and 8 (fig. 6a and 6b). Stocking rates of 1.5-3.0 hd/ha are supported in the more favourable mesotherm areas represented (zones 15 and 19, fig. 6a and 6b).

Some data from nitrogen-fertilized grass pastures are included for comparison. Increases in beef production and stocking rates of the order of 100% are possible with the use of high rates of nitrogen fertilizer in the better megatherm and megatherm/mesotherm environments (fig. 6c). Liveweight gains per head are little greater than for the average legume-based pasture however (fig. 6c).

Relationships between the steer stocking rate and liveweight gain data and the growth x green index for legume-based pastures (fig. 7) are similar to the relationships described for the sheep experiments. The divergence of the production per hectare and per head trends with increases in the growth x green indices between mesotherm and mesotherm/megatherm environments is similar. These data also show the stocking rates and production levels for megatherm areas compare closely with those in megatherm/mesotherm zones at similar index levels (fig. 7).

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Discussion

Brougham: Could the Nix classification be also applied to the United States and NZ?

Helyar: Henry Nix has built up a data bank in Canberra to allow him to map the world using his bioclimatic indices.

Marten: You mentioned that it is hard to prevent C_4 grasses from dominating clovers. They also have this problem in Hawaii. Could you comment further?

Helyar: The problem is one of retaining the clover to continue supplying N in the face of rapid kikuyu growth. Kenya white clover appears to be able to compete better than white clover in warmer environments where the C_4 grasses tend to dominate.

Barnes: Do you have information on differences between Kenya white clover and white clover on growth characteristics, disease resistance, etc.?

Helyar: Controlled temperature-glasshouse work shows Kenya has a similar optimum temperature for growth to white clover, but the decline in growth rate at increasing temperatures above the optimum is not as rapid.

Being strongly tap-rooted, Kenya white clover plants are more susceptible to attack by Amnemus and white fringed weevils. Kenya white clover stands can also be devastated by slugs.

Roughley: Are there differences in plant habit that contribute to differences in competitive ability?

Helyar: In mixtures, Kenya white clover stolons can twine and climb better than those of white clover. This allows the species to compete better for light.

Easton: Does this difference in habit affect the capacity for regrowth following defoliation?

Helyar: Kenya white clover, being a stoloniferous clover, does respond to grazing pressure. Medium to high grazing pressure is needed to ensure persistence, but not high enough to graze the legume out. More research is needed on grazing management of these pastures.

Minson: Why don't NZ recommendations for pasture management apply in Australia?

Helyar: In most of Australia, the very seasonal type of environment requires a stocking rate in the wet season low enough to enable feed to be carried over into the dry season. Under these conditions (annual species, low grazing pressure in the growing season) rotational grazing has generally not shown any advantage over set stocking.

Burns: Can parts of a property be managed differently, i.e., intensive in some areas and extensive in others?

Helyar: In ley farming areas this is done. Cropping areas are used to save pasture. These options mean higher legume content can be maintained in annual pastures than in the perennial environment.

Clements: You gave us a single profile of white clover. What are the chances of using variability of legumes in plant breeding programs to improve the efficiency of their use?

Helyar: Mike Curll at Glen Innes has been studying white clovers with longer petioles. These give the clover a better competitive ability with perennial grasses. Selections from NZ are not well adapted probably because homoclimates in the two countries are rare. In Australia, breeding programs are probably required in each of the unique bioclimatic environments.

Minson: The Nix climate studies allow one to delineate areas where different legumes might be grown in different parts of Australia. Does the Nix system take into account the low reliability of rainfall in Australia? How would this low reliability affect the possibility of extrapolating Nix's Australian climate criteria for legumes to the United States? Have you any warnings?

Helyar: The Nix bioclimatic classification includes terms for the mean annual growth index and terms describing the variation of the mean monthly growth and moisture indices. Hence both the mean and seasonality effects are accounted for. If, by reliability of rainfall, you mean the variability of the rainfall for a given month (or week) from year to year, then Nix's classification does not account for this. For coastal environments in eastern Australia, rainfall reliability at a given time in the subtropical areas is less than in either the tropical or the temperate regions. On the final question about warnings--where the rainfall in a given month is unreliable, the soil moisture storage capacity becomes important for plant persistence during dry periods. In general, a less predictable rainfall is less valuable for plant growth, especially when associated with soils of low available moisture capacity.

The Distribution and Use of Forage Legumes in New Zealand

J.A. Lancashire[1]

Abstract

Over 80% of the forage legume seeds sown for agricultural use in New Zealand are white clover. The species is sown in nearly all pasture mixtures and high buried seed loads in many districts ensure that white clover is present in most grazed pastures.

Major limitations to the successful use and widespread distribution of white clover are seasonal and annual dryness, fertility, poor soil (particularly phosphorus and pH levels), uncontrolled grazing management, and low winter temperatures. Some of these may be overcome through increased sub-division, fertiliser applications, and new white clover cultivars; but high costs now limit these remedies in some environments and farming systems.

As a result, increased use of alternative legumes such as red clover and lucerne for improved summer production in dry areas, Lotus pedunculatus for low fertility moist hill country, subterranean clover and other annual clovers for dry hill country, and alsike clover for high country, is expected to occur. These developments will be greatly assisted by the recent release of new cultivars with much improved agronomic performance.

Introduction and Historical

Of the Leguminosae, 121 taxa have been reported (Webb 1980) as naturalised in New Zealand, with records of a further 11 unsubstantiated. Half of these species will probably have been grazed by ruminants at some time, but less than 10% are now deliberately and regularly sown in pasture mixtures; i.e., white clover (Trifolium repens L.), red clover (T. pratense L.), lucerne (Medicago sativa L.), subterranean clover (T. subterraneum L.), lotus (Lotus pedunculatus Cav., L. uliginosus Schkuhr., L. major), alsike clover (T. hybridum L.) and strawberry clover (T. fragiferum L.).

The annual, suckling clover (T. dubium Sibth.) is still frequently sown as a contaminant in white clover lines (80/20 mixtures of white clover/ suckling clover are a cheaper alternative to pure lines of white clover). Suckling clover was very highly regarded as the most valuable of the pioneer legumes on a wide range of low fertility soils (Levy 1930). Its role as a winter-spring producer has been graphically described by the noted farmer-naturalist H. Guthrie-Smith from Hawke's Bay as the only plant which stood between him and his bank manager for 60 years (Guthrie-Smith 1969).

A number of other annual clovers, e.g., clustered clover (T. glomeratum L.), striated clover (T. striatum L.) and haresfoot trefoil (T. arvense L.), are widely distributed, particularly in dry hill country, and some are still being introduced as contaminants in white clover lines or more commonly in the low-cost impure 'station' or 'bush-burn' seeds mixtures. Clustered clover and striated clover are well grazed by stock in winter and spring and are generally found on drier sites than suckling clover. Haresfoot trefoil exists as a pioneer legume on extremely dry, low fertility soils and is not liked by stock, particularly when mature (Levy 1930, Saxby 1956).

Annual lotus (L. hispidus L. or L. sauveolens Pers.) was widely used as a pioneer legume (lines also frequently contained L. angustissimus L.) in dry low fertility soils in northern New Zealand in the early part of the century (Levy 1918), while the perennial birdsfoot trefoil (L. corniculatus L.) was sown in small quantities and strongly recommended for sowing on light land in Canterbury (Hilgendorf 1918).

Annual serradella species, especially Ornithopus pinnatus (Miller) Druce, are common as volunteers in grazed pastures on low fertility sandy coastal soils in Northland. Halliwell (1960) considered that seed was probably accidentally introduced during the last century by gumdiggers from Mediterranean countries and had since established on 120,000 ha of coastal soils. Excellent cool season production of good quality feed made it a highly valued plant by farmers on these soils (Halliwell 1960). Wild serradella (Ornithopus perpusillus L.) occurs as a fairly vigorous prostrate plant in grazed spring pastures on dry faces on hill country pumice soils in parts of the central volcanic plateau.

A number of medics and melilots have been either deliberately sown (Saxby 1956) or introduced in tailings sown after burns (Guthrie-Smith 1969), and are still sometimes seen in pastures particularly in drier areas suitable for lucerne. Black medic (Medicago lupulina L.) is generally found in understocked areas because it is favoured by grazing animals (Madden 1951), while spotted burr clover (M. arabica L.) and burr clover (M. hispida L., M. polymorpha L.) are actively avoided by stock and may become dominant (Levy and Davies 1930, Madden 1951, Saxby 1956).

Both sweetclover (Melilotus alba Medik.) and yellow sweetclover (Melilotus officinalis [L.] Pall.) were formerly reported as common in New Zealand (Fairfax-Cholmeley 1915). The biennial sweetclover was used deliberately in agriculture, apparently with some success as an alternative to lucerne on very dry alkaline soils (Fairfax-Cholmeley 1916, Sellwood 1946). Sweetclover and the King Island melilot (Melilotus indica L. All.) were recommended for initial pasture establishment on sand country (Levy 1922), but were generally regarded as not being very acceptable to grazing animals (Cockayne 1915).

The perennial strawberry clover is still occasionally used on poorly drained or saline soils where it may out-produce white clover (Davies 1962) particularly in the cool season. Lotus major (L. uliginosus Schkuhr., L. pedunculatus Cav.) has been very widely and successfully used as a pioneer

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legume, particularly under lax grazing in moist (850-2,500 mm annual rainfall) low fertility hill country (Suckling 1966, Levy 1970). However, once established it can also survive well in drier areas providing grazing pressure is not too severe (Madden 1951).

Current Distribution of Pasture Legumes

Seed Sown

New Zealand has 9 million ha of sown pastures on hill and flat land and 4.5 million ha of native grassland (mainly high country which carries only 5% of the national stock units; Brougham and Grant 1976). In the past 10 years 200-400 thousand ha have been resown or oversown annually with the approximate quantities of the major legume species shown in table 1.

Table 1 - Pasture legume seeds sown in New Zealand 1974-83 (Annual)

Species	Tonnes sown	Seed rate (kg/ha)	Area sown (ha)
White clover	1,200	3	400,000
Red clover	220	3	74,000
Subterranean clover (last 5 years)	100	3-6	20,000-30,000
Lucerne	300	10	30,000
Lotus pedunculatus[1] (last 8 years)	10	3	3,000
Alsike[2] (last 3 years)	30-50	3	10,000-20,000

[1]This is probably an overestimate of agricultural usage, as substantial quantities have been sown on road cuttings and in forests.

[2]Guesstimate, as much seed is traded between farmers.

The dominant position of white clover is shown by a survey of 157 pasture seeds mixtures in the Southern North Island (table 2).

Table 2 - Percentage of legume species in 157 pasture mixtures sown in Southern North Island autumn 1968 (Harris 1969)

Species	Occurrence (%)
White clover	98.7
Broad red clover	58.6
Montgomery red clover	14.6
Subterranean clover	19.7
Lotus	4.5
Others[1]	7.0

[1]Includes alsike clover, strawberry clover, and other species.

The national dominance of white clover among the pasture legumes is confirmed by the seed sales of a major N.Z. seed company (table 3). The main difference between the North Island and South Island is the replacement of some white clover by alsike in the high country regions in the South. Otherwise white clover sales did not differ markedly between wet and dry regions, although the highest sales of lucerne (10%) were in the drier and/or pest-prone areas in the central volcanic plateau, Central Otago and Canterbury. In the dry east coast areas of Gisborne, Hawke's Bay, and Wairarapa, and in Nelson-Blenheim, red clover (20%-25%) became an important component, although these figures are inflated because some of the areas are used for seed production.

Table 3 - Percentage of legume seed sales (% by weight) by a major New Zealand seed company

Species	North Island	South Island
White clover	70	57
Red clover	16	15
Subterranean clover	8	4
Lucerne	3	7
Alsike		15
Others	3	2

Pasture Surveys

There is very little good quantitative information on the legume composition of mixed pastures in the different farming regions of New Zealand. Hilgendorf (1935) and Madden (1940) carried out descriptive pasture surveys of the North and South Islands in an attempt to measure agricultural progress. Pasture types were described in terms of species composition and their interaction with broad environmental and management variables. Suckling (1949) surveyed the distribution of species on untopdressed Wellington hill country and found that there was considerably more suckling clover than white clover on both sunny and shady faces.

A largely unpublished pasture survey in 7 farming classes in the Manawatu in 1968 showed that the frequency of occurrence of white clover was lowest in hill country (40%-50%) and highest in terrace and flat land farms (70%-80%). Other legumes were fairly insignificant with the exception of suckling clover, which occurred at frequencies of 10%-20% in spring on hill and sand country sheep farms, but because of its annual habit was hardly present at all by summer. A similar pattern was displayed by subterranean clover on both sheep and dairy farms on sand country, with levels of 10%-20% in spring. Red clover was rarely found and never exceeded 5% for any area and then only in dairying or lowland sheep situations. Lotus species occurred with a frequency of between 1% and 5% on hill country and sand country.

Buried Seed Loads

Buried seed loads offer a good general guide to the distribution of some legume species throughout farming districts and regions of New Zealand, although the slower seed development of red clover and Lotus pedunculatus, compared with white clover, subterranean clover and other annual legumes like suckling clover (Suckling 1966), will obviously influence seed loads. Work by E.O.C. Hyde showed that a 6-week spell (absence of grazing) ensured a good natural re-seeding of white clover in hill country pasture, while a summer spell of up to 3 months was required for adequate re-seeding of red clover and Lotus pedunculatus. Subterranean clover did not require a rest period as it can re-seed under close grazing (table 4).

Generally the levels for white clover buried seed loads were higher in wetter areas and under cattle grazing, while subterranean clover was higher in drier areas and under sheep grazing (table 5). Lotus was only common in higher rainfall areas while suckling clover was generally high at all sites but lower in cattle pastures than sheep pastures. Other important annual legumes included clustered clover, which was as high as 120 kg/ha on coastal sand country and 40 kg/ha on dry hill country. As rainfall increased, levels fell off very rapidly so that no seed was found in the higher rainfall hill country. Striated clover was not as widely distributed as clustered clover but the very high levels of around 200 kg/ha present in dry hill country again fell to zero in higher rainfall areas (F.E.T. Suckling, unpublished data). More recent data collected at a number of high fertility dry hill country sites (Olsen P ca. 20; pH 5.5-6.0) confirm that these trends are still present (table 6). In general about 90% of the white clover seed at these sites was hard seed, but after scarification only 50% of this seed proved viable on a sunny face at Taupo compared with 90% on a shady face.

Shrubby Legumes

Recent studies have demonstrated the important role of goats in controlling the spiny legume shrub gorse (Ulex europaeus L.) a serious weed on up to 700,000 ha of New Zealand's hill country (Batten 1979, Lambert et al. 1981). Sheep will also eat gorse under high stocking rates, particularly at the seedling stage, but goats utilise it much better when the plant is more mature (Radcliffe 1984).

Table 4 - Effect of management practices on buried seed populations of legumes (kg/ha) in hill pasture with medium summer rainfall (from Hyde and Suckling 1953)

Management	White clover	Subterranean clover	Suckling clover	Lotus
Rested from grazing:				
(a) Unimproved pasture set-stocked	0.4	0	13	0
(b) As in (a) but rested Jan.-March for one year	3.8	0	23	0
Legumes oversown, superphosphate applied, and rested from grazing:				
(a) unimproved	.76	0	14.8	0
(b) oversown, fertilised but set-stocked	1.14	14.3	12.9	0
(c) as in (b) but rested Jan.-March for one year	44.6	14.3	81.0	3.7

Table 5 - Minimum and maximum levels of buried legume seeds in soils of New Zealand pasture (kg/ha) (from Hyde and Suckling 1953 and F.E.T. Suckling, unpublished data)

Pasture type	White clover	Red clover	Subterranean clover	Lotus	Suckling clover
Intensively stocked lowland pastures:					
Cattle pastures	3-25	0-2	0-58	0-0.6	0.7
Sheep pastures	0-10		0-693		0.25-180
Coastal sand and shingly soils prone to summer drought	0-16		50-689		4-179
Coastal sand prone to winter floods	3-16		22-491		0-102
Gumland clay (N Auckland)	0-63	0-4		0-8	0-39
Pumice soils--free draining	1-384	0-2		0-11	1-174
Unploughable hill pastures:					
High summer rainfall (1,600-2,400 mm annually)	0-4.6	0-13	0-7.2	0-26	0.5-62
Medium summer rainfall (1,000-1,600 mm annually)	0-2.3	0-2	7-22	0-0.4	6-73
Low summer rainfall (under 1,000 mm annually)	0-0.5	0-2	0-639	0-0.3	9-73

Calculations are based on the following thousand-seed weights: white clover (0.71 g), red clover (1.97 g), subterranean clover (6.75 g), lotus (0.50 g), and suckling clover (0.50 g).

Table 6 - Buried seed loads of legumes in topdressed dry hill country (kg/ha)

Species	Wairarapa	Taupo		Turakina
		Shady Face	Sunny Face	
White clover	1.75	22.7	14.1	0.5
Striated clover	22.0			
Clustered clover	25.8			30.0
Suckling clover	78.3	2.0	8.2	1.0
Subterranean clover	154.8			
Wild serradella			10.1	

The development of a relatively spineless gorse (DSIR Annual Report 1982) and the fact that other shrubby legumes like broom (Cytisus scoparius [L.] Link) are also grazed and are very well adapted, particularly to the drier eastern areas of New Zealand (Williams 1981), has renewed interest in their useful role in agriculture. This could include increased feed supply, particularly in dry periods, increased nitrogen fixation, shelter (for plants and animals), and slope stabilisation (M.G. Lambert, personal communication). The more erect-growing shrubs like tree lucerne (Chamaecytisus palmensis [Christ] Hutch) may also have potential, but there are considerable problems in combining effective utilisation by grazing animals and long-term plant production and survival (Logan 1982).

Use of Pasture Legumes

White Clover

White clover is widely used in all improved grasslands throughout New Zealand, and other authors in this workshop will consider more fully aspects of white clover production and environmental and edaphic limitations.

Although broad optimum grazing managements for white clover in New Zealand have been well documented (Brougham et al. 1978), particular modifications may be necessary in some environments. The widespread adoption of "all-grass" farming and year-round rotational grazing in the cool moist lowland environment of Southland has led to a drop in the contribution of white clover. On 20-year-old pastures it has been found (Hay and Baxter 1983) that set stocking over spring for 12 weeks, combined with 4-week rotations over summer, doubled white clover yields compared with pastures rotationally grazed throughout the whole period (table 7).

White clover yields can be increased by grazing with cattle (Grant et al. 1978) and goats (Clark et al. 1984) and by decreased frequency of defoliation, particularly in moist summers (Brougham 1959, Brock 1974). Although some of these techniques have application in hill country (Bircham 1977, Grant et al. 1978), recent work has shown that the most widely used white clover cultivar, 'Grasslands Huia' (90% of sowings), does not persist well in hill country (Forde and Suckling 1977) particularly under sheep grazing (M.G. Lambert, personal communication). On 5 moist and dry hill country sites Charlton (1984) found that only 12% of Huia plants remained after 3 years from sowing. The development of the smaller-leaved cultivar, 'Grasslands Tahora', with much greater stolon density and persistency for these generally moist, moderately fertile hill country environments (table 8), should assist in improving the white clover content in at least 3 million ha of hill country (Williams et al. 1982).

Trials over a wide range of soil types (Radcliffe 1974, 1975; Hoglund et al. 1979) have shown white clover to be particularly responsive to summer rainfall, and unable to respond to decreased defoliation intervals in dry periods (Lancashire 1974). This deficiency of white clover in up to 3 million ha of seasonally dry, flat and hill country in New Zealand (Williams et al. 1978) may be ameliorated by the development of more tap-rooted, drought-tolerant types (Lancashire 1978), or genotypes that persist through annual re-seeding (Macfarlane and Sheath 1984).

Lucerne

Yield advantages of lucerne-based pastures over white clover-based pastures have been demonstrated in many N.Z. environments in areas with an annual rainfall of 400-750 mm (Lancashire 1975), on very free-draining soils (e.g., sands and pumice country) (Baars et al. 1975, Smith and Stiefel 1978) with a higher rainfall of 1,200-1,300 mm, on grass grub (Costelytra zealandica White) prone soils (Mace 1980) and on heavier soils with a 1,000 mm rainfall (Theobald and Ball 1983).

In addition to increased production of high quality feed (Rattray et al. 1976) lucerne also greatly reduces the annual variation in pasture production common in ryegrass-white clover pastures in drier areas (O'Connor et al. 1968). However, the advantages of well managed stands are much less in wet years (+19%) than dry years (+51%) (Dunbier et al. 1982).

Table 7 - Effect of spring management on white clover yields (kg DM/ha) (Hay and Baxter 1983)

Spring treatment	White clover Spring (%)	White clover Summer (%)	White clover Summer Yield	Total annual yield and (%) white clover
Set-stocked	10	28	1,780	15,500 (19)
Grazed 2 weekly	5	21	1,300	15,500 (15)
Grazed 3 weekly	6	15	400	15,950 (11)
Grazed 4 weekly	6	11	660	17,000 (8)
Set-stocked spring and summer	10	15	880	15,000 (12)

Table 8 - Relative growth scores of hill country white clover to 'Grasslands Huia' (100) (Corkill et al. 1981)

Location	Growth score
Low fertility moist hill country:	
Ballantrae, sunny aspect	153
Ballantrae, shady aspect	175
High fertility, seasonally-dry lowland	66

As a consequence, the lucerne area increased very markedly from well below 100,000 ha in the mid-1960's to 220,000 ha in 1976 (Dunbier et al. 1982). Although part of this increase was caused by the growth of the Japanese market for dried lucerne meal, considerable increases in the areas devoted to hay, silage and grazing also occurred. However, since the peak was achieved there has been an equally rapid decline, so that the total area is now probably only around 120,000 ha. This decline has been attributed to a big increase in pests and diseases that reduced the stand life of susceptible cultivars, a series of wet seasons and the collapse of the lucerne meal market (Dunbier et al. 1982).

A number of other agronomic disadvantages are also apparent in lucerne-based pastures. There has been a failure to develop successful, stable and repeatable combinations with other grasses to offset the very low winter production of lucerne. Unless satisfactory autumn rains occur, it is difficult to successfully establish annual ryegrasses like 'Grasslands Tama' (Lolium multiflorum Lam), and, if this is achieved, grass growth must be controlled in the spring if lucerne is not to be adversely affected (Vartha 1972). Similar problems have been associated with over-drilled cereals (Baars and Douglas 1976). Many perennial grasses such as 'Grasslands Roa' tall fescue (Festuca arundinacea Schreb) and 'Grasslands Matua' prairie grass (Bromus catharticus Vahl) have proved too competitive with lucerne (McQueen and Baars 1980, Fraser and Vartha 1980) although the summer-dormant 'Grasslands Maru' phalaris (Phalaris aquatica L.) is promising (Fraser and Vartha 1980).

The decline in the lucerne area has also been related to the high cost of establishing and maintaining a stand, particularly with the use of herbicides (Talbot 1982); susceptibility to mis-management, particularly in wetter areas (White 1982); the development of improved systems of management for ryegrass-white clover pastures (Wall 1982) and the use of other pasture mixtures like 'Matua' prairie grass and 'Grasslands Pawera' red clover (Trifolium pratense L.), which combine high summer and winter production (Lancashire 1978, Hay et al. 1978) (table 9).

On dry uncultivated hill country the problems encountered on flat land are compounded. It is difficult to achieve successful oversowing (Baars et

Table 9 - Red clover and mixed sward yields in Southland (kg DM/ha) (Hay et al. 1978, Hay and Ryan 1983)

Species	Spring	Summer	Autumn	Winter	Total
Cool temperate moist environment (rainfall 936 mm):					
Ariki perennial ryegrass/ Huia white clover	7,000	4,100	2,500	1,200	14,800
'Tama' annual ryegrass/ Pawera red clover	6,000	5,000	1,500	2,000	14,500
Pawera red clover	4,500	7,100	1,200	750	13,550
Cool temperate dry environment (rainfall 760 mm):					
	Spring	Summer	Autumn/Winter		Total
Ruanui perennial ryegrass/ Huia white clover	3,240	3,245	1,895		8,380
Pawera red clover	3,240	3,900	1,245		8,385
Matua prairie grass/ Pawera red clover	3,540	4,830	3,195		11,565

al. 1982) and costs of establishment may be 70% greater than for conventional pasture (Musgrave 1983). However, the considerable advantages obtained on low, sunny country in North Otago (550 mm rainfall) in providing reliable spring feed were worthwhile (Musgrave 1983).

The development of new cultivars resistant to important pests and diseases such as bacterial wilt (Corynebacterium insidiosum), verticillium wilt (Verticillium albo-atrum) and the blue-green aphid (Acyrthosiphon kondoii Shinji) should help to extend stand life (Dunbier and Easton 1982), but it appears that in the immediate future the lucerne area in New Zealand will tend to stabilise as a special purpose monoculture in traditional areas, for grazing or hay and silage production. These are low rainfall, flatland regions of the South Island and higher rainfall, very free-draining pumice soils on the central volcanic plateau.

Red Clover

Traditionally red clover has been a short-term component of most permanent pasture mixtures in New Zealand and generally disappears after 2-3 years. In the early stages of pasture development it often dominates white clover during summer and autumn because of its greater tolerance of drought and low fertility and more erect growth habit (Sears 1962, Brougham 1965). It is intolerant of close and frequent grazing (Brougham 1960) and significantly lower yielding than lucerne on free-draining soils with low annual rainfall (550-800 mm) (Sheath et al. 1977, Williams et al. 1978). However, the ability to produce high yields of good quality feed in mixed swards in higher rainfall areas at the same time of the year as lucerne and under a wider range of fertility conditions gives red clover some distinct advantages (Lancashire 1975, 1978) (table 9).

The greater persistency of the tetraploid red clover 'Pawera' under both mowing (McDonald 1971) (table 10) and farm grazing (Hay et al. 1978, Brougham 1981, Lancashire et al. 1982) compared with the diploid cultivars 'Hamua' and 'Turoa' suggests that the species now has the potential to persist for at least 4-5 years in commercial farming. This increased field persistency appears to be associated with improved resistance to crown rot (Sclerotinia trifoliorum) and possibly stem eelworm (Heterodera trifolii) (Anderson 1973). However, if Pawera is grazed in winter on wet soils and the crown is damaged, crown rot and root rot (Verticillium dahliae) may reduce the stand persistency to only 2 years (J.A. Lancashire, unpublished data; R.A. Skipp, personal communication).

Table 10 - Red clover yields (kg DM/ha) in a mixed sward after 5 years under mowing in Otago (McDonald 1971)

Red clover	Clover yield	Total
Turoa	850	11,550
Pawera	4,480	12,570
Hamua	1,350	11,300

Subterranean Clover and Other Naturalized Annual Clovers

Many cool-season legumes (with the exception of suckling clover) are generally found in the drier hill country regions of New Zealand, although they are also often significant on sunny faces in higher rainfall hill country (1,500 mm) (Suckling 1975, Lambert 1977, Macfarlane and Sheath 1984). Subterranean clover is generally regarded as a pioneer legume on moderately fertile dry lowland (Madden 1951, Sears 1962, Levy 1970) and is replaced by other more productive legumes as fertility improves (Scott 1979). However, general observations (Brougham et al. 1973, Williams et al. 1978) and very limited production data (see table 11) suggest that the species is still very important in some lowland situations. Information on the year-to-year contribution of subterranean clover and the other annual legumes in farm systems on dry hill country is not well documented. However, the preliminary results shown in table 11 suggest that subterranean clover is an extremely important component at some sites in some years, while clustered clover and striated clover (E.W. Vartha, personal communication) can also be significant. At most sites the contribution from white clover was relatively low and illustrates once again the deficiencies of the current cultivars in these environments.

The annual re-seeding habit of these clovers enables them to survive hot dry summers, and the dominance of clustered clover and striated clover (Vartha et al. 1982) at 2 sites is probably the result of their flowering and setting seed earlier than subterranean clover and white clover (before the onset of drought). In future it may be possible to extend the distribution of subterranean clover into these areas by the use of earlier flowering cultivars (Macfarlane and Sheath 1984) and controlled grazing during winter (Vartha et al. 1982).

In high country the use of subterranean clover is probably limited by low temperature or frost (Scott 1979), and it does not generally survive above 1,000 m in the South Island (Musgrave 1977).

Suckling clover is well adapted to low fertility areas (Brock 1970) and is very widely distributed. In these situations it may outyield white clover and Lotus pedunculatus in winter and spring (Brock 1970, Grant and Lambert 1979), but its annual yield is lower and considerably less than subterranean clover in hill country (Suckling 1960). However, the lack of published yield information makes it difficult to assess suckling clover's contribution to farming, although traditional measurement techniques will probably underestimate its potential (Smetham 1977).

Lotus pedunculatus Cav.

The role of lotus as a pioneer legume is well established in New Zealand (Montgomery 1938, Suckling 1966, Levy 1970), but the increased cost of fertilisers has recently renewed interest in this

species for the development of acid (pH <5.2), phosphate deficient, South Island tussock grasslands (Scott and Mills 1981). There are up to 2 million ha of this country and the yield advantages of the tetraploid lotus cultivar 'Grasslands Maku' over Huia white clover are shown in table 12. This superiority of lotus has been attributed to more efficient use of available phosphate (Brock 1970) and a greater tolerance of exchangeable aluminium in the soil (Nordmeyer and Davis 1977). Its usage is probably restricted to the higher rainfall (1,000 mm +), sub-humid zone (Scott and Charlton 1983) and standing herbage may suffer frosting at higher altitudes.

In higher fertility farming areas white clover is better adapted (table 13) and regrowth after defoliation is much superior (Sheath 1981). However, the range of micro-sites in moist hill country and the recent decline in superphosphate and lime applications suggest that lotus could be included in seeds mixtures to help maintain the legume component (Charlton and Brock 1980).

Alsike Clover

This is one of the principal legumes used in the South Island high country for oversowing tussock grassland and in developed pastures both for grazing and hay. It requires moderate to high fertility and appears to be able to survive over a number of years through prolific re-seeding (Scott 1979). Its

Table 11 - Maximum recorded legume composition (%) for a range of dry sites under grazing

	Wairarapa (annual figures)			Taupo (spring figures) Set-stocked		Turakina (spring figures)
	Hill country		Flat	Sunny	Shady	Set-stocked
	Set-stocked	Rotational	rotational	face	face	sunny
White clover	10	9	18	2	4	6
Subterranean clover	34	11	22			8
Suckling clover			1	9	1	3
Clustered clover						15
Wild serradella				6		

Table 12 - Lotus and clover yields three years after oversowing on a range of tussock grassland sites (kg DM/ha) (Scott and Mills 1981)

District	Altitude (m a.s.l.)	pH	Maku lotus	Huia white clover	Lotus : clover ratio
Waipori	610	4.6	4,990	1,520	3.3
Berwick	420	4.6	1,090	420	2.6
Waiora Farm	550	4.6	3,080	1,120	2.8
Rockland Station	800	4.9	930	120	7.7
Danseys Pass	914	5.0	1,690	580	2.9
Danseys Pass	609	5.5	1,670	1,130	1.5
Tara Hills[1]	475	5.5	4,480	3,020	1.5

[1]Sunny face; trial on shady face failed owing to frost heave.

Table 13 - Effect of superphosphate on Maku lotus/Huia white clover balance (kg DM/ha) (Brock and Charlton 1978)

Superphosphate (kg/ha)	Lotus	Clover
0	2,730	1,860
200	1,530	2,710

herbage is more tolerant of frost than is white clover's and because of its hollow stem it conditions more rapidly than red clover for hay production. It appears well adapted to the extensive grazing systems in the high country, but will not tolerate close and frequent defoliation (Smetham 1977).

Other Legumes Under Evaluation

A very large number of other legume species are currently being researched in New Zealand (Charlton 1983), but only two, birdsfoot trefoil and sainfoin (Onobrychis viciifolia Scop.), have had recent commercial evaluation. The potential role of birdsfoot trefoil is on laxly grazed, moderate fertility, dry hill and high country, which is not suitable for lucerne and 'Maku' lotus, and where other legumes like red and white clover and alsike clover do not persist (Scott and Charlton 1983). The role of sainfoin has been evaluated as a non-bloating alternative to lucerne on dairyfarms on the central volcanic plateau, where the latter species occupies around 25% of the farmed area (Mace and Peterson 1979). Despite being more tolerant of some of the pests and diseases which affect lucerne, yields of sainfoin have been low and considerable weed problems have been encountered (Percival and McQueen 1980).

Many legumes of warm temperate and subtropical origin have been evaluated in Northland but only two, Trifolium semipilosum (Kenya white clover) and Lotononis bainesii, appear to have potential under grazing (Rumball and Lambert 1980). Kenya white clover also showed promise as a perennial legume on sand country (Williams et al. 1978) along with a number of other annual clovers of Mediterranean origin.

A number of species of serradella have been evaluated as winter annual forage legumes on sandy coastal soils. Experimental lines of pink serradella (Ornithopus sativa Brot) outyielded other serradella species and subterranean clover by at least 2,000 kg DM/ha (25%), but did not reseed successfully (Williams et al. 1976). In Northland the species is showing promise as a winter legume break crop between maize and other cereals (Taylor et al. 1979).

Improved lupin cultivars (Lupinus angustifolius L.) have shown promise for summer forage (Burtt and Hill 1981) and tick beans (Vicia faba L.) for cool season production (Janson and Knight 1980).

In the South Island high country two species, crown vetch (Coronilla varia L.) and Caucasian clover (Trifolium ambiguum Bieb), are showing potential on low-to-moderate fertility soils. Although both are very slow to establish, excellent swards have been obtained after 5 years (Scott 1979, Lucas et al. 1981).

Conclusions

The long-term aim of grasslands development in New Zealand expounded by Sir Bruce Levy (1936) was to produce an environment capable of supporting a simple ryegrass-white clover pasture. In most areas this involved clearance of bush and forest vegetation, very heavy fertiliser topdressing and sub-division and controlled grazing. The fact that white clover has achieved such a dominant position is a tribute to Levy's foresight, farmer skills and the plant's extremely wide adaptability. However, factors such as increasing fertiliser costs, the major effects of drought on New Zealand's pastoral productivity, topographic variation in hill country and the relative immaturity of many soils (e.g., sands and pumice), suggest that there will be a greater use of legumes alternative to white clover in the future. The improved agronomic performance of recently-released cultivars of red clover, lotus and lucerne will aid this development, but there is still a need to pursue vigorously plant improvement programmes in both alternative legumes and, not least, white clover, in order to optimise forage performance in the wide range of farming environments in New Zealand.

Research Needs

1. There is an urgent need to quantify the yield and persistency of legumes, particularly the annual species, in farm pastures in different environments throughout New Zealand.

2. Limitations to white clover growth and persistency in different farming environments throughout New Zealand need to be more clearly defined.

3. Programmes to improve the adaptability of white clover and the agronomic performance of alternative legumes should be accorded high priority.

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Discussion

Clark: Would you care to comment on whether experimental techniques or choice of sites has tended to underestimate the value of annual legumes in New Zealand?

Lancashire: I believe they both have. There is also an emotional bias against annuals. Even farmers with a large proportion of subterranean clover do not realize the contribution it is making. Further, research is not carried out on farm pastures in areas where annuals are growing, and measurement techniques often do not measure the contribution of annual legumes. Too much published work refers only to sites where white clover performs well.

Collins: Subterranean clover is presumably low-key in New Zealand--only Tallarook and Mt Barker are used. What is the potential for increasing the area grown?

Lancashire: All seed, ca. 100 tonnes/year, is imported from Australia. Mt Barker and Woogenellup are the dominant cultivars. There is a current trial examining a range of sub. and white clover types.

Sheath: Interest in sub. clover arises from its persistence in harder areas. Typing of naturalized North Island populations suggest that Mt Barker is sufficiently early flowering. There is no benefit in earlier flowering types than Woogenellup.

Stern: With the range of climate in New Zealand, what sort of range in maturity dates has been selected for in annuals?

Lancashire: No selections have been made. There is a range in flowering times of the naturally occurring annual legumes; e.g., clustered clover is often earlier than sub. clover.

Sheath: Haresfoot trefoil in the south is much the same. If flowering is later (mid-December), drought can have a serious effect and white clover can be restricted.

Rumbaugh: Are shrub legumes seen as having an important role in grazing systems? If so, what problems occur?

Lancashire: We are right at the beginning of this program. We are looking at the range in types of tree lucerne.

Syers: Tree lucerne, especially its high roughage content, is thought to have potential for deer farming. Any comments?

Lancashire: I don't know why it should be specific to deer farming; perhaps the browsing habit of deer would improve utilization.

Barnes: You referred to Levy and his philosophy. To what extent is there interest in mixtures of trees and pasture, and what legumes are used in these systems?

Lancashire: Farm forestry is being researched at present. *Pinus radiata* is the sole tree species. It is hard to envisage farmers combining high-quality trees and high-quality pastures, but plantings, particularly of small wood lots, will increase. Research on pasture species for hard sites has been stimulated by the opinion, often stated, that such areas are suitable only for trees. Areas in the central North Island were converted from pasture to trees in the late 1960's following devastating droughts. Current knowledge of different pasture species would have ensured that these areas would have been planted in more appropriate pasture species at the outset. The shade-tolerant 'Maku' lotus is one legume being researched for agroforestry.

Brougham: Agroforestry is currently subject to much discussion in this country, as is the role of forage legumes.

The Distribution and Use of Forage Legumes in the United States

William E. Knight[1]

Abstract

In the United States, a diverse array of forage legume species is available that fits well into livestock production systems as a source of grazing, hay, silage, and greenchop. The diverse climatic and soil conditions across the seven major continental regions and the tropical areas necessitate this diversity in forage legume resources. No single legume species is dominant in all the described regions. Alfalfa, Medicago sativa L., is the most widely grown forage legume, occupying an estimated 12-13 million ha. Red clover, Trifolium pratense L., is the most widely grown of the true clovers and occupies an estimated 6 million ha. White clover, T. repens L., is widely distributed in many pastures of the temperate United States, with an estimated 5 million ha. Birdsfoot trefoil, Lotus corniculatus L., is increasing in importance in several regions of the United States and has replaced alfalfa and red and white clover in some areas. Other forage legume species are important in that they fill special needs in maximizing the utilization of U.S. grassland resources. Some of these legumes are arrowleaf clover, T. vesiculosum L.; subterranean clover, T. subterraneum L.; rose clover, T. hirtum All.; crimson clover, T. incarnatum L.; vetches, Vicia spp.; annual and perennial lespedezas, Lespedeza spp.; sweet clovers, Melilotus spp.; and some important tropical species.

Introduction

Between 1950 and 1970, research on clovers (Trifolium spp.) and special-purpose legumes was greatly reduced in the United States; in the last decade, however, interest was rekindled in the use of legumes in pastures and in conservation tillage systems (Pederson and Knight 1983, 1984). The energy crisis and subsequent price increase for inorganic nitrogen stimulated part of this interest. An emphasis on better quality forage with better seasonal distribution also contributed to renewed interest in forage legumes.

Recent economic conditions have created keen competition for land resources. Commodity crops have replaced pastures, resulting in shortages of and high prices for forage legume seed. Erodible land has been planted in row crops, resulting in unacceptable losses of soil. There is national concern over excessive soil losses and the need for improved conservation tillage systems (Work Planning Conference on Legumes in Conservation Tillage Systems, Lincoln, NE, January 11-13, 1983). Legumes for pasture and cover constitute an integral part of these soil-conserving systems.

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In the the United States, a diverse array of forage legume species is available that fit well into livestock production systems as a source of grazing, hay, silage, and greenchop. Alfalfa, Medicago sativa L., is the most widely grown forage legume in the United States, with an estimated 12-13 million ha (Hanson and Barnes 1973). Red clover, Trifolium pratense L., is the most widely grown of all the true clovers (Taylor 1973, Smith and Taylor 1984). It is grown for hay, pasture, and soil improvement and fits well into 3- and 4-year rotations. It occupies an estimated 6 million ha in the United States. White clover, Trifolium repens L., is the most important legume in many parts of the temperate zone (Leffel and Gibson 1973). It is estimated that 5 million ha of white clover are seeded annually and that it volunteers in over 20 million ha of grassland in the United States. Other important species are birdsfoot trefoil, Lotus corniculatus L.; rose clover, Trifolium hirtum All.; subterranean clover, Trifolium subterraneum L.; crimson clover, Trifolium incarnatum L.; arrowleaf clover, Trifolium vesiculosum Savi.; vetches, Vicia spp.; and lespedezas, both annual (Lespedeza striata Hook & Arn. and L. stipulacea Maxim.) and perennial (L. cuneata Don.). Still other species are important in various regions of the United States. For example, A.E. Kretschmer in Florida has an extensive program involving over 4,000 accessions of tropical legumes (Pederson and Knight 1983). These species have great potential for improving tropical pastures in Florida and are basic to grassland agriculture in Hawaii (Rotar and Plucknett 1973).

The following discussion is divided by the regions contained in Heath et al. (1973) as shown in figure 1.

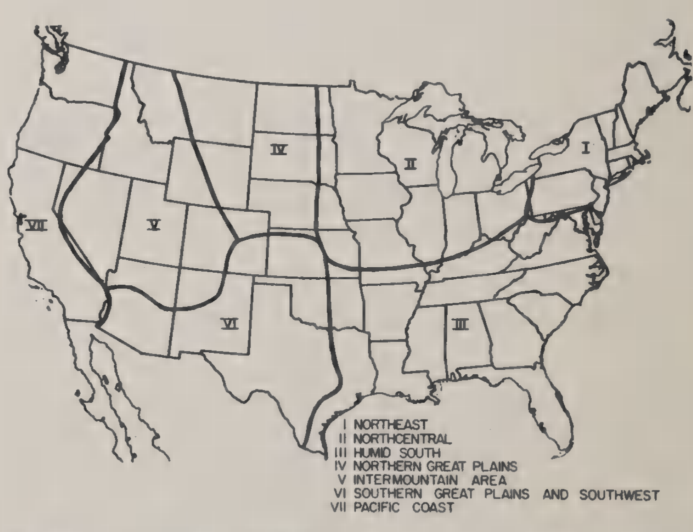

Figure 1—Regions of the continental United States.

Northeast Region

Brown and Baylor (1973) have discussed the role of forage legumes in northeast region agriculture. Ruminant livestock is the primary source of agricultural income. The variable nature of northeastern soils requires careful choice of legume species and cultivars; low winter temperatures significantly affect the choice of perennial species. Alfalfa is the most widely used legume in

the Northeast and is commonly utilized in a multiple-harvest system as hay, silage, or greenchop. Red clover is useful in short rotations that often include a small-grain companion crop. Red clover will grow on soils that are either too acid or too wet for alfalfa. Birdsfoot trefoil is grown for hay or silage and is especially well suited to the less well-drained soils of the northern part of the region. It will normally outlive red clover by several years. Ladino clover is used in the region for rotational pasture, but the hectarage has declined in recent years. There is some alsike clover, T. hybridum L., utilized in the region; however, its use is declining in favor of birdsfoot trefoil. In recent years, crownvetch, Coronilla varia L., has shown promise as a pasture and silage legume for the Northeast.

North Central Region

According to Heath (1973), the eight Central and Great Lakes' States include soils formed under both prairie and forest vegetation. This large region is one of the most fertile areas to be found on the continent. It is well adapted to the production of corn and forage and produces approximately two-thirds of the U.S. corn and soybeans. The average freeze-free summer period is from 100 days in the north to 190 days in the south.

Alfalfa is the most important legume in terms of producer interest and use of improved practices. The greatest concentration of alfalfa hectarage is in areas having the larger numbers of dairy animals, including Wisconsin, Minnesota, Iowa, and Michigan.

Second to alfalfa, red clover is used widely, primarily as hay in mixtures. It is grown by dairymen and beef producers where alfalfa production is a problem. It is a good legume in beef forage programs as summer pasture and as winter feed, utilized as stockpiled in late fall and early winter grazing and as hay field-stored in large round bales. In terms of hectarage, white clover is the third most important because it is indigenous in most pastures, primarily as volunteer common white clover. Some ladino is occasionally included in pasture seedings. Birdsfoot trefoil is of fourth importance, and its use has gradually increased. Alsike clover and crownvetch are used in the region, but they are of minor importance. In the southern part of the region, Korean lespedeza, Lespedeza stipulacea Maxim., is grown extensively as pasture and hay on soils of poor to fair productivity.

Humid South

The humid south is characterized by Chamblee and Spooner (1973) as having a relatively high rainfall of 1,250 mm or more per year, with erratic distribution between and within years, and neither drought nor excessive moisture is uncommon. The growing season in the upper South ranges from 175 to 200 days and, in the lower South, from 210 to 260 days. In the lower South, mild winters are conducive to year-round grazing, while in the upper South little forage is produced in December, January, and February. Perennial grasses are the basic pasture plants in the region. In the upper South, the dominant species are tall fescue, Festuca arundinacea Schreb; orchardgrass, Dactylis glomerata L.; and Kentucky bluegrass, Poa pratensis L.; while in the lower South the major species are bermudagrass, Cynodon dactylon (L.) Pers.; bahiagrass, Paspalum notatum Flugge; dallisgrass, Paspalum dilatatum Poir.; and carpetgrass, Axonopus affinis Chase. Cool-season perennial forages reach their peak production from March 1 to June 1, with a lesser second peak in September and October. Warm-season perennials produce their forage between May 1 and September 1. Basically, there are four forage systems used in the humid South. These are (1) perennial and annual grass species grown without a legume and fertilized with nitrogen, (2) perennial grass species grown with a perennial legume, (3) perennial grass species overseeded with winter annual legumes with or without annual grass, and (4) winter annual grass or cereal and winter annual legume grown on a prepared seedbed. Producers and scientists have been developing grazing systems, utilizing legumes, in which the cow harvests most of the feed that is consumed. In these systems, a minimum amount of feed is harvested, stored, and fed back to the animal.

In the upper part of the humid South, red clover is the dominant perennial legume species, followed by white clover and alfalfa. White clover is the dominant perennial legume in the lower South. This is particularly true if indigenous stands are considered. In recent years, the use of birdsfoot trefoil has been increasing.

The hectarage of alfalfa and alfalfa-grass mixtures declined rapidly in the South with the advent of the alfalfa weevil, Hypera postica Gyll. At present, interest has increased in alfalfa production, but substantial increases in hectarage have not yet occurred.

In the upper South, ladino clover-grass mixtures are generally more productive than intermediate white clovers. However, the intermediate white clovers are used in the lower South to assure reseeding where drought stress may cause stand failures on light-textured soils. In general, mixtures of dallisgrass-white clover, tall fescue-white clover, and bahiagrass-white clover are especially well adapted to the moister soils, whereas the bermudagrasses and lespedezas are best adapted to the well-drained, deep, drier soils.

The winter annual legumes most often used for forage production in the South are crimson, arrowleaf, subterranean clover, and ball clover, T. nigrescens L. For maximum growth, winter annual clovers must be seeded in late summer or early fall and properly fertilized. They may be grown alone, but are usually grown in mixtures with tall fescue, cereals, or annual ryegrass, Lolium multiflorum Lam. Hairy vetch, Vicia villosa Roth; lupines, Lupinus L. spp.; bigflower vetch, Vicia grandiflora var. kitaibeliana W. Koch; and crownvetch are used as cover crops and provide limited grazing in some management systems.

Summer legumes used in the South include both annual and perennial sericea lespedeza. Alyce clover, Alysicarpus vaginalis DC., is used in the lower

South and in Florida. The tropical species used in Florida are discussed further on.

Northern Great Plains

Newell and Moore (1973) emphasize the great extremes in climate, soil, and natural vegetation of the midcontinent area. Climate and soil factors largely control the choice of small-seeded grasses and legumes seeded for hay and pasture. This diversity of environment requires special procedures of farming and ranching, including dryfarming methods, grazing management, and irrigation practices. The growing season varies from 160 days in the southeast to 110 days in the northwest. Along the eastern border of the Great Plains region, hay and pasture crops are parts of general diversified farming systems. Most farms have fields of alfalfa and smooth bromegrass or natural grasslands utilized for hay and pasture. Perennial grasses and legumes constitute most of the useful permanent cover in the Great Plains.

Alfalfa is the principal legume hay of the region. It is usually grown on the best soils, frequently with irrigation, and is the principal high-protein feed for balancing the hay ration. Its production provides the dominant forage crop for export to other areas in the form of dehydrated alfalfa used in mixed feeds. South Dakota harvests over 800,000 ha of alfalfa for hay. Sweetclover, *Melilotus alba annua* Coe. and *M. officinalis* Lam., is seeded in the Great Plains for use either as green manure or as a combination pasture and soil-improving crop. In the Dakotas, it is often utilized as hay or silage. It is drought resistant and also grows well in parts of the Great Plains receiving as much as 430 mm of rainfall.

Other legumes associated with grasses on low wet soils are red clover and alsike clovers. Birdsfoot trefoil, either grown alone or in grass-legume mixtures, is increasing in importance. Mixtures of birdsfoot trefoil with sainfoin, *Onobrychis viciaefolia* Scop., have given good yields in short rotations in Montana. Sainfoin is recommended in Montana for pastures on dryland areas that receive 330 mm or more of annual precipitation.

Intermountain Area and Alaska

The intermountain area is described by Keller and Klebesadel (1973) as predominantly mountainous terrain, with intensively cropped land in scattered valleys having access to water for irrigation. Dryfarming is practiced on higher land where the soil is deep and heavy enough to hold moisture. The climate is Mediterranean, with average precipitation about 350 mm per year, but ranging from less than 120 mm in the drier valleys to over 1,250 mm in the higher mountains.

Alfalfa is the most important crop. Hay is produced primarily on irrigated land, but some is also produced on dryland farms. A modest percentage of hayland is still seeded to red clover. Red and alsike clovers are grown on sites too wet for alfalfa. They are especially valuable in mountain meadows.

Destruction of alfalfa by the alfalfa weevil has caused an increased interest in other legume species as possible substitutes. Among these legumes are sainfoin; Cicer milkvetch, *Astragalus cicer* L.; and sickle pod milkvetch, *Hedysarum boreale* Nutt.

Cicer milkvetch is a very winter-hardy species adapted to conditions ranging from irrigated drylands that receive no more than 400 mm of annual precipitation. It is also adapted to a wide range of soil types and tolerates slight acidity to moderate alkalinity. Sainfoin is well adapted to the dry, calcareous soils of the northern Rocky Mountain region of the United States that receive at least 300 mm of annual precipitation and on sites with limited irrigation.

In Alaska, forage crops are grown to support the State's dairy, beef, sheep, and swine operations. Growing-season temperatures, although somewhat lower than in midtemperate latitudes, are conducive to growth of cool-season crops. Land suitable for pasture is estimated at 2 million ha. Perennial and biennial legumes commonly grown in more southern latitudes frequently winterkill. Therefore, grasses are grown principally in monoculture and fertilized with N. Canadian field peas, *Pisum arvense* L., are grown with oats, cut only once, and preserved as silage.

A significant amount of native rangeland is utilized in Alaska. Two native legumes among the forbs are the abundant nootka lupine, *Lupinus nootkatensis* Donn., on uplands and the less common beach pea, *Lathyrus maritimus* L., along many shorelines.

Southern Great Plains and Southwest

Climatic variation in the Great Plains and Southwest is described by Herbel and Baltensperger (1973). Precipitation not only varies greatly within and among seasons and years but also among locations separated by only a few kilometers. Because of erratic weather conditions, farming is high risk in all but the eastern portions of the region. However, because of the favorable temperatures, irrigated farming is highly productive where good-quality water is available. A high percentage of the land in the region is used for ranching.

Alfalfa is the most important forage legume in the region; it requires a large amount of water for maximum production, however. Alfalfa and perennial grasses are well adapted for the improvement of desert and semidesert soils for irrigated agriculture. Alfalfa is especially valuable in crop rotation systems in the irrigated parts of the region.

Pacific Coast

Hafenrichter et al. (1973) state that all but a small part of the Pacific Coast States where farms and ranches are found is essentially arid or semiarid. The area west of the Cascade Mountains and the high plateaus in eastern Oregon and Washington and adjacent Idaho are classed as subhumid. Even in the humid and subhumid areas, the climate is dry in summer and supplemental irrigation

is required to maintain season-long forage production.

Alfalfa is the principal hay crop in the Pacific Coast States. Much of the hay in the region is harvested from seed fields. The first crop is harvested for hay and the second for seed. Red clover is seeded with ryegrass, and alsike is used with grass on poorly drained land and on acid soils. Oats and vetch or oats and pea mixtures are grown west of the Coast Ranges in Oregon and in western Washington. Birdsfoot trefoil is also grown in mixtures with grass for hay in irrigated areas.

A large part of the land in the Pacific Coast States and Idaho is grazed. Pastures on farms are either permanent, cropland, or supplemental. Extensive areas of pasture in the foothills of California are occupied by exotic winter annual grasses and legumes that thrive in the Mediterranean climate.

In the Mediterranean climate zone, selection of legume species is determined by soil type and availability of irrigation. Ladino clover: narrowleaf trefoil, Lotus tenuis Waldst. & Kit.; woollypod vetch, Vicia dasycarpa Tenore; and subterranean and rose clovers are used in addition to alfalfa. These species may be grown in combination with tall fescue, orchardgrass, bermudagrass, or hardinggrass, Phalaris aquatica L.

In the continental climatic zone, alfalfa is grown on well-drained deeper soils and birdsfoot trefoil on poorly drained sites. Each species is grown in association with a grass such as tall fescue or orchardgrass.

For the subhumid part of the continental climatic zone, white clover, 'Grassland Huia,' is recommended with orchardgrass, tall fescue, or perennial ryegrass, Lolium perenne L. On droughty soils, subterranean clover or alfalfa is used. White clover and birdsfoot trefoil are used on poorly drained sites. Strawberry clover, T. fragiferum L., has also been introduced into some areas of the Pacific Coast that have wet saline and alkaline soils.

Legumes in Tropical and Subtropical Areas

Tropical and subtropical areas of the United States include Hawaii, southern Florida, coastal areas on the Gulf of Mexico, Puerto Rico, U.S. Virgin Islands, Guam, and American Samoa. Rotar and Plucknett (1973) describe the extreme diversity of climates and forages grown within these areas. This paper presents only a summary of some of the major species used in the tropical areas.

Hawaii

The general approach to forage production in Hawaii has been to utilize legume-based pastures rather than to rely on fertilizer N for the grasses as in Puerto Rico. The most productive legume-grass mixtures in Hawaii have been koa haole, Leucaena leucocephala (Lam.) deWit., and guineagrass, Panicum maximum L.; greenleaf desmodium, Desmodium intortum (Link) DC., and pangola digitgrass, Digitaris decumbens Stent.; kaimi clover, Desmodium canum (Gmel.) Schintz & Thellung, and kikuyugrass, Pennisetum clandestinum Hochst. ex Chiov.; and white clover and kikuyugrass. Other legumes that show promise are stylo, Stylosanthes guianesis (Aubl.) Scv.; glycine, Neonotonia wightii (R. Grah. ex Wight & Arn Verdcourt); centro, Centrosema pubescens Benth.; siratro, Phaseolus atropurpureus DC.; and big trefoil, Lotus pedunculatus Cav.

Southern Florida

In Florida, tropical legume species have been evaluated for adaptation (Pederson and Knight 1983). Improvement in Stylosanthes spp. is in progress at Fort Pierce. A.E. Kretschmer has evaluated forage legume introductions in the genera Aeschynomene, Desmodium, Arachis, Macroptilium, Desmanthus, Leucaena, and Centrosema. Currently, there is little use of these species, primarily because of seed production problems.

Summary

A diverse array of forage legume species is available that fit well into livestock production systems as a source of grazing, hay, silage, and greenchop. In the United States, alfalfa is the most widely grown forage legume. Red and white clovers are grown extensively in the temperate zone, and interest in birdsfoot trefoil is increasing. Annual legumes are used to extend the grazing season in the humid South and to provide self-regenerating stands in regions with Mediterranean climate.

Research Needs

Exploitation of the legume resource available to U.S. livestock production will require an expansion of multidisciplinary research teams. Centers of excellence should be developed in the various regions to enhance the germplasm resources available and to develop grazing systems to fully utilize the potential of forage legumes in animal production.

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Discussion

Stern: What evaluation procedures are used for the wide range of species and environments?

Knight: Procedures are essentially similar, though regional variations occur. Plant introductions are screened and numbers reduced rapidly. Promising legumes are sown in pastures at satellite stations where animal evaluations are carried out as soon as possible. One recent example of an exception was Berseem clover, where a 25-percent survival in a cold winter occurred which was unexpected. Material was quickly multiplied and released without animal evaluation due to demand.

Roughley: Subclover was not successful initially due to Rhizobia problems. Are all the new clovers being introduced screened for Rhizobia requirements?

Knight: Yes. This is being done jointly with an N company but we now have a microbiologist in the group, and we regard Rhizobium inoculants as very important. Some earlier introductions may have been discarded because of nodulation failures.

Barnes: There has been a reduction of 50 percent in legume research over a decade. What is your assessment of the present situation?

Knight: There has been a marked change. Recent update of a 1977 survey in 1983 and 1984 in the southern region of the United States shows impressive increases in the number of locations looking at legumes. These are mostly dealing with evaluations; there was little input into breeding until recently. The increase has been mainly on the part of the States, with the Federal side remaining about constant.

Brougham: There was a big effort on Lotus corniculatus in Northeastern United States 20 years ago which was stopped. What happened to the plant material?

Marten: Recently, two new full-time positions have been added at St. Paul, MN, on birdsfoot trefoil in breeding and seed production. Liaison with Guelph is included.

Brougham: What happened to germplasm from lotus program? Was it lost?

Knight: No. Germplasm was maintained in two ways: (1) Regional Plant Introduction Station collections and (2) national seed storage facility. Performance results were lost in a lot of cases. Records are more carefully kept now.

Barnes: As the legume breeding program expands, is there any move to obtain new germplasm?

Knight: Yes. Elizabeth and Warren Williams stirred interest in T. ambiguum, and two explorations are being planned for perennial Trifolium species. We are looking at new sources of germplasm and this is being encouraged by the USDA.

Rumbaugh: USDA maintains a germplasm acquisition program. There have been at least 4 collections trips with 3,000 accessions recently.

Reid: Crimson clover doesn't recover from grazing. In terms of winter hardiness, are you looking at Persian clover which has similar hardiness and production to Berseem?

Knight: Crimson clover does recover from grazing until the reproductive stage begins. There are two problems with Persian clover: (1) very high bloat problem as quickly indicated by the N fertilizer companies; (2) it is very susceptible to alfalfa weevil. However, since it is successful and evident on roadsides and elsewhere, it needs a new look.

Helyar: I was impressed by the demonstration of annual legumes killing off C_4 grasses. Why does this happen?

Knight: A winter annual legume is grown on a dormant summer sod. If a farmer doesn't graze off the Ball and Arrowleaf clovers, the summer active grasses are shaded out.

Sheath: When I was in the lower south United States recently, it was evident that the grazing operation centers around the beef cow/calf operation for feedlots. Is this inherently low-intensity grazing system likely to continue, or will there be a change to finishing cattle on grass?

Knight: The predicted change during the energy crisis has not occurred in general. It has been researched, but animals finished in feedlots demand a higher price at present.

Barnes: This is a contentious point at present. Factors affecting any change are the price of energy/oil and grain crops (namely corn), and consumer preference for grain-finished beef. If forage production efficiency continues to increase and energy prices remain high or increase, then beef finishing on forage should increase in the future.

Marten: There is a consumer bias against yellow fat in beef as produced from legume/grass finishing.

Productivity and Economics of Legume-Based Versus Nitrogen-Fertilized Grass-Based Forage Systems in Australia

R.J.K. Myers and E.F. Henzell[1]

Abstract

Inputs of legume and fertilizer nitrogen (N) into forage systems in Australia and the productivity and economics are examined. Direct comparisons made between the systems are reviewed, and future research needs are highlighted. The annual input of N by legumes in permanent pastures in Australia about 10 years ago was estimated to be 1.5 Mt N, and for pastures in rotation with crops 0.5 Mt N. The amount of fertilizer N used recently on pastures and forage crops is 35 kt per year.

The persistence, productivity and area of legume-based pastures in southern Australia are declining due to reduced use of superphosphate and increased cropping intensity in pasture-grain crop rotations. Drought, pests, diseases and soil acidity may also be involved. In northern Australia, legume-based pastures have not been sufficiently profitable to stimulate rapid development, except in the dairy industry. N is frequently applied to grass pastures in the dairy industry throughout Australia as a means of boosting production in the cooler months.

Future research in southern Australia should aim to give an adequate appraisal of different pastures in terms of animal production, to find annual legumes better suited to new grain cropping systems, to increase cool season production of legumes and to improve the efficiency of use of legume and fertilizer N in grazed pastures. In the tropics, research should concentrate on more profitable legume-based pasture systems, ley-farming or legume-intercropping systems, diseases, legumes for clay soils, and legumes that will withstand heavy grazing. For N-fertilized grass, research problems include the lower feeding value of grasses compared with legumes, the large losses of N from N-fertilized pastures, and the question of the long-term N fertilizer requirement of grasses.

Introduction

Nitrogen fixation by phosphate-fertilized subterranean clover and annual medics was a major factor in the large increase in livestock numbers that occurred in Australia after World War II. Australia's flocks and herds increased from 222 M livestock units (number of sheep + 7 x number of cattle) in 1951 to a peak of 383 M units in 1976. In addition, the nitrogen (N) fixed by these legumes increased the yield of cereal crops grown in rotation with them (Donald 1982).

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Livestock numbers have since declined by 23 percent to 294 M units (1983) and there is now concern about the declining condition of legume-based grass pastures in temperate and mediterranean environments of southern Australia.

In northern Australia, grazing of beef cattle is the major livestock industry. The pastures there (predominantly of native grasses) still depend primarily on the mineralization of old soil organic matter for their N supply. These pastures are generally deficient in N and the need for suitable tropical pasture legumes has led to the search for and subsequent identification of a range of productive cultivars. Just when the use of tropical legume-based forage systems appeared to have entered a phase of rapid expansion, in 1973, the profitability of the beef industry slumped.

This paper presents figures for the inputs of legume and fertilizer N to Australian forage production, examines the current productivity and economics of legume- and fertilizer-N-based systems, reviews the results of experimental comparisons between them, and highlights some future research needs.

Nitrogen Inputs

Donald (1982) estimated that the annual contribution of N by legumes in Australia, during the period 1971-2 to 1975-6, was about 1.5 Mt in the fertilized permanent pastures and 0.5 Mt by pastures in cereal crop rotations. These estimates were based on the relation between N fixation and superphosphate usage. The contribution of legume nitrogen has probably decreased since 1976, because 22 percent less superphosphate was applied to pastures during the period 1977-8 to 1981-2 than during the five years examined by Donald (fig. 1) and because of various agronomic problems mentioned later in this paper. An alternative estimate based on an area of 24 M ha currently containing effective legumes and an average annual rate of fixation of 50 kg N ha^{-1}, gives an annual N contribution by legumes of about 1.2 Mt (J.S. Pulsford, personal communication).

Very little fertilizer N was used on pastures and forage crops in Australia prior to world War II (De Groot and Pulsford 1983). Post-war, its use increased significantly, chiefly for dairy production. It has usually been too expensive for the sheep and beef cattle industries, though some has been used in fat lamb and dairy beef production.

The whole of Australian agriculture used only about 0.25 Mt per year during the three years to 1982. It has been estimated (J.S. Pulsford, personal communication) that 35 kt of N were used on forages throughout Australia in 1981-2 (table 1). The dairy industry used about four-fifths of this and most of the remainder was used for beef and fat lamb production. About two-thirds was applied to long-term pastures and one-third to forage crops and short-term leys. New South Wales (NSW), Queensland (Qld) and Victoria (Vic.) were the major users.

Data for the consumption of N fertilizer during the past 17 years (fig. 1) show that N use on long-term pastures was highest over the period 1968-73,

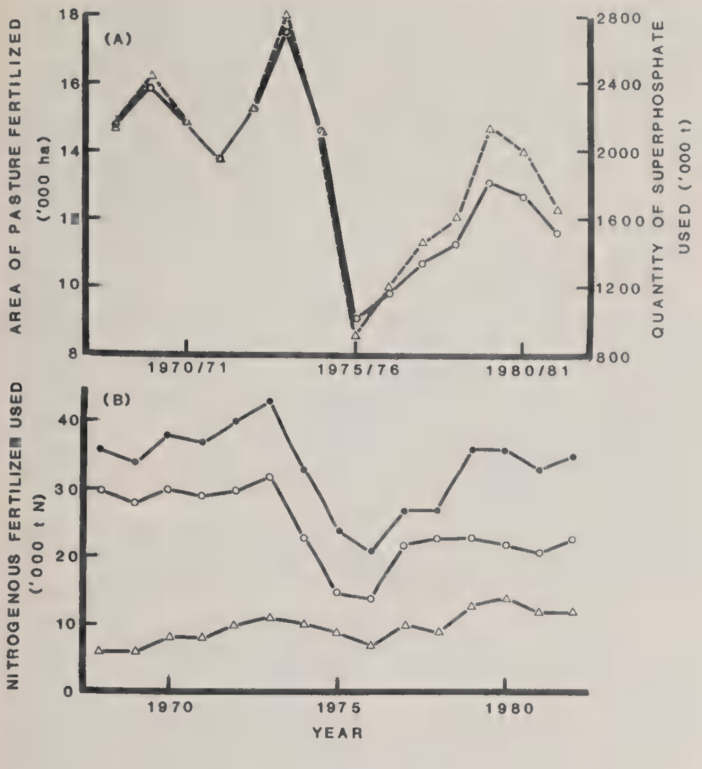

Figure 1--Fertilizer use on Australian pastures. (A) superphosphate--area fertilized (Δ----Δ) and quantity used (o____o), (B) nitrogenous fertilizer--quantity of N used on pastures (o____o), forage crops (Δ____Δ) and the total (●____●).

Sources: Australian Bureau of Statistics (A) and J.S. Pulsford (personal communication) (B).

Table 1 - N fertilizer usage for livestock production--Australia 1982 ('000 tonnes N)

State	Pastures		Forage crops		Total
	Milk	Meat	Milk	Meat	
Queensland	4.3	0.9	2.4	1.0	8.6
New South Wales	5.3	.6	2.4	.7	9.0
Victoria	5.3	.7	1.0	.6	7.6
Tasmania	.2	...	.1	.1	.4
South Australia	1.2	.4	1.1	.4	3.1
Western Australia	3.5	.3	2.0	.6	6.4
Australia	19.8	2.9	9.0	3.4	35.1

slumped in 1974 and 1975 and has not returned to the earlier level. The use of N on forage crops and short-term leys did not suffer as large a decrease in the mid 1970's and now exceeds the earlier level. These trends are closely correlated with the profitability of the Australian dairy industry (see later).

Productivity and Economics

Mediterranean and Temperate Legumes

There is no accurate information for the area of forage legumes grown in Australia, however, a maximum of 40 M ha of crop and pasture land has grown forage legumes at some time during the last thirty years. Of this, about 16 M ha of acid and neutral soils has been sown to subterranean clover (Donald 1970), but we do not have information on the area of the other forage legumes (e.g., annual medics) used in the rainfed sheep and wheat lands. Legumes of this kind are particularly important on neutral to alkaline soils in the drier part of the wheat-growing zone in the states of Western Australia (WA), South Australia (SA), Vic. and NSW (extending into southern Qld). In NSW the area of sown medic pasture is small (about 4 percent of the area of one shire) and is in decline. However, in central NSW naturalized medics were particularly widespread (Andrew and Hely 1960). In 1981-82, 12.2 M ha of pasture was fertilized with superphosphate (fig. 1). Since most of this area would have carried annual forage legumes, and since not all legume pastures would be fertilized every year, the area of pasture containing subterranean clover and annual medic in significant quantities is clearly substantial. Most of this area would have carried annual forage legumes.

Information provided by State Departments of Agriculture indicates that there is concern in southern Australia about the decline in area, persistence and productivity of the clovers and medics. This decline has been caused largely by socio-economic factors. The continuing cost-price squeeze on Australian producers caused them to reduce expenditure on pasture inputs during the 1970's, including purchase of superphosphate (fig. 1), and the greater profitability of grain growing relative to wool and meat production caused them to increase their cropping intensity. In WA, for instance, many farmers who grew wheat one year in three, now grow it three years out of five. The increased emphasis on grain cropping in the annual legume areas of NSW has, on some farms, led to the complete abandonment of a pasture rotation.

Even where a rotation has been retained, cropping has disrupted the normal reproductive cycle of the pasture, and this, plus heavier grazing at the time of seed formation, has resulted in a decline in soil seed reserves. The decline in the productivity of annual forage legumes has been exacerbated by the recent drought, new and more damaging pests and diseases, and increasing soil acidity (Carter et al. 1982).

At the same time as the areas of legume ley have been declining, an increasing amount of fertilizer N has been used on dryland cereal crops in Australia. Use on wheat, oats and barley increased from 20×10^3 t N in the three years to 1968, to 79×10^3 t N in the three years to 1981 (De Groot and Pulsford 1983). While superphosphate-fertilized annual legumes remain profitable in the rainfed sheep and wheat lands of southern Australia, they are not as profitable as they were in the 1950's and 1960's.

The chief temperate legumes of the higher rainfall and irrigation areas are white clover and lucerne (alfalfa). About 5.8 M ha of grassland in Australia include some white clover (R.J. Clements, quoted by Mathison 1983). While the white clover pastures of the present dairying areas are generally in good condition, the productivity of those on the former dairy pastures of northern NSW and southern Qld has decreased to a low level. In Tasmania, following five consecutive years or below average rainfall, the legume content of pastures has declined, primarily because of the poor persistence of white clover (J.G. Stephens, personal communication).

The area of lucerne cut for hay has decreased from an average of 255×10^3 ha for the five years ending in 1975-6 to 121×10^3 ha for the five years to 1981-2. This decrease is partly due to aphid infestations, although resistant varieties have since been introduced. In the higher rainfall areas of SA, there has been increasing use of Namoi vetch (Vicia villosa) and shaftal clover (Trifolium resupinatum) (I.D. Kaehne, personal communication).

The role of cool-climate legumes in the Australian dairy industry requires special comment. This industry has been traditionally pasture based and variable costs are lowest on farms that rely mainly on pasture for their feed supply (Earle 1982, Chopping et al. 1982). Australian dairy farmers experienced severe economic difficulties in the early and mid 1970's, but milk prices have since risen significantly (Habgood 1982, Thurbon and Morton 1982). Increasingly efficient use of forage legumes has accompanied the recovery of the industry. On the Atherton Tableland of north Qld, for instance, the percentage of irrigation farmers using substantial areas of clovers increased from nil in 1976 to 43 in 1981 (Chopping et al. 1982). Such legume-based systems are economically sound (Busby and Van Beek 1982) and Earle (1982) has predicted that forage legumes will in future play an even more important part in the Australian dairy industry.

Tropical Legumes

Qld accounts for over 90 percent of the improved pastures in northern Australia. The area in Qld has increased steadily, attaining a maximum of 3.9 M ha in the mid 1970's. These statistics do not include areas where townsville stylo and annual medic have become naturalized following accidental introduction (Weston et al. 1981). The improved pastures of the statistics consist chiefly of grasses (e.g., buffel grass, Cenchrus ciliaris) much of it on fertile soils that formerly carried Acacia forests. The sowing of such pastures continues; tropical and temperate legumes were included in the seeds mixture on only 27 percent of the 182×10^3 ha of new pasture sown in 1982-3.

These tropical sown grass pastures have helped support increased livestock numbers in Qld, the total rising from 65 M units in 1951 to a peak of 94 M units in 1978. The subsequent fall to 78 M units in 1983 has been proportionally smaller than in the rest of the country, though even in Qld the expansion of cropping has taken some of the best grasslands. Nearly half of the current sown pasture land may be subject to cultivation as crop areas expand (Weston et al. 1981). It has been estimated that the relatively small area of sown pasture in northern Australia (1-2 percent of the total) has contributed 10 to 15 percent of the pastoral productivity (Mott et al. 1981) and up to 24 percent of the annual beef production (Mannetje 1984), although pasture deterioration and losses to crop production in recent years suggest that these figures should be revised downwards (J.J. Mott and R. Reid, personal communication).

About 50×10^3 ha of legume forage crops have been sown annually in Qld during recent years. More than half the area has been sown to various tropical species (until recently dominated by Siratro, but now with an increasing proportion of new stylo cultivars). The remainder has comprised temperate species, chiefly lucerne and white clover (grown with irrigation to provide winter feed for dairy cattle) and the annual medics (in southern areas where sufficient winter rainfall is received).

The annual tropical legume townsville stylo (Stylosanthes humilis), a chance introduction to Australia like subterranean clover and the annual medics, spread naturally onto or was sown on a total of about 0.6 M ha in northern Australia. During the 1970's, however, the productivity of these pastures was greatly reduced by anthracnose disease. About 0.2 M ha of Siratro have been sown in Qld, but cattlemen have experienced great difficulty with persistence of this twining species, whose productivity is extremely susceptible to overgrazing. Only a minor proportion of the pasture originally sown with Siratro now contains a high percentage of the legume (Walker 1983).

At the present relatively low beef prices, even productive Siratro pastures are insufficiently profitable to be financially worthwhile (Van Beek 1983). Only Fitzroy stylo (Stylosanthes scabra cv. Fitzroy), aerially seeded into native grassland, offers an internal rate of return greater than 20 percent per annum, which is considered to be the minimum acceptable to the industry (Brown 1983, Wicksteed 1983). The Fitzroy stylo technology is still relatively untested.

The performance of tropical legume pastures has generally been much more satisfactory on dairy farms, provided they have been large enough or have had sufficient other feed to maintain a safe stocking rate, which in the case of the Atherton Tableland is <1.6 cows ha^{-1} (Davison et al. 1982). Such legume pastures give satisfactory economic returns per cow (Busby and Van Beek 1982).

Nitrogen-Fertilized Grass

In contrast to the concern that exists about the current condition and performance of many legume-based forage systems, the standard of fertilizer-N-grass-based forage production systems in Australia has improved considerably in recent years. As described above, this development is closely linked with the improving productivity and profitability of the Australian dairy industry.

In southern Australia, most of the N is applied to

nominally legume-based pastures to boost production during the cooler months, when temperatures are not so cool as to prevent grass growth, but when the N input from legumes is drastically reduced. An effort is usually made to fertilize the most grassy swards. The grass species is usually a ryegrass, but there is significant N fertilization of kikuyu in NSW and of paspalum and kikuyu in WA.

In northern NSW and Qld, most of the N is applied to annually sown ryegrass or forage oats, growing during the period from late autumn to spring. About 40% of the N applied to Qld pastures in 1982 (table 1) was used on perennial tropical grasses. The economic return from the use of N for milk production in Qld, on either temperate or tropical grasses, irrigated and rainfed, has recently been very satisfactory (Busby and Van Beek 1982).

Earle (1982) concluded that a greater use of N fertilizers by the Australian dairy industry offers scope for further productivity gains in the future. In contrast, there appears to be very little likelihood of greater use of fertilizer-N-based forage systems in the Australian wool and beef industries, unless there is a marked relative change in costs and commodity prices. Even in one of the most favoured rainfed grassland environments of eastern Australia (the coastal lowlands just north of Brisbane), at the high beef prices of March 1973, N-fertilized-grass systems of beef production had internal rates of return of only 11.3 to 12.9 percent (Firth et al. 1974). Moreover, these systems required very large investments and their profitability was extremely sensitive to changes in the price of fat cattle.

Comparison of Systems

Productivity

Experiments with forage systems in Australia have shown that (a) the potential dry matter yield of N-fertilized-grass systems is generally higher than that of legume-based systems, especially in the sub-tropics and tropics, and (b) the grass in legume-based systems is N-deficient for much of the time. The latter point is proven by the high frequency of immediate grass yield responses recorded when fertilizer N has been applied to legume-based pastures (Newman et al. 1962). Cocks (1980) calculated that about 59% of the shortfall of productivity in a grazed 40 years old subterranean clover-based pasture in SA was due to N deficiency in the grass. Reed and Cocks (1982) concluded that pastures were more likely to respond to N if the legume content was below 20%.

Higher forage yields with fertilizer N are not necessarily reflected in higher livestock production. We believe there are two reasons for this. The higher feeding value of legumes may compensate for a slightly lower herbage yield. Secondly the design of many grazing experiments has not provided for adjustments to stocking intensity to allow adequate utilization of the fertilized herbage (A.K. Stubbs, personal communication). In Australia, there have been surprisingly few direct comparisons between legume/grass and N-fertilized grass pasture. In a short-term comparison of animal production from legume-based pastures with and without N fertilizer in Victoria, Stockdale and King (1980) applied N to irrigated pastures containing a mixture of white clover, ryegrass, cocksfoot and paspalum. The response to N was dependent on the stocking rate, declining from 17 to 3 kg DM/kg N as stocking rate increased from 4.4 to 8.6 cows ha^{-1}. However, increased pasture production was not reflected in increased total output of dairy products, except for milk protein. Lower nutritive value of the N-fertilized pasture could in part explain the lack of response (King and Stockdale 1980).

On the north coast of New South Wales, data obtained by Mears and Humphreys (1974) show that in a two-year study the stocking rate for maximum liveweight gain per hectare was increased by N fertilizer from 4.7 to 10.2 weaners ha^{-1}. Maximum liveweight gains on the kikuyu-white clover pasture increased from 502 to 1,280 kg ha^{-1} per year.

In northern Australia, Jones (1974) found that the gain per ha of beef cattle at optimum stocking rates in an N-fertilized system was 1.9 times that of the tropical legume system. At a lower-rainfall site, Mannetje found that Siratro-buffel grass gave about the same beef production per hectare as buffel grass fertilized with sufficient N for near-maximum forage yield (Jones et al. 1983). Other comparisons between systems with beef cattle in coastal Qld yielded the following annual liveweight gains per ha: N, 650: legume, 511 (Mellor et al. 1973); N, 1,106: legume, 507 (Bryan and Evans 1971); N, 585: legume 450 (Grof and Harding 1970).

Busby and Van Beek (1982) combined data from separate dryland grazing experiments on the Atherton Tableland of Qld and used as the basis of their economic calculations a milk yield of 5,352 L ha^{-1} from tropical legume pasture stocked at 1.6 cows ha^{-1} and 7,500 L ha^{-1} from grass stocked at 2.5 cows ha^{-1} and fertilized with 400 kg N ha^{-1} yr^{-1} (Davison et al. 1982). An experiment with irrigated pastures near Rockhampton in Qld resulted in average daily milk yields between July and November of 14.6 L from clovers (white and subterranean), 14.5 L from clovers and ryegrass, and 13.9 L from ryegrass receiving 57 kg N ha^{-1} each 24 days (Murray and Chopping 1982).

Economics

The results of Bryan and Evans (1971), summarized above, indicated a more than two-fold difference in productivity in favour of the fertilizer N system. Despite this large difference there was only a small difference in the internal rate of return. For the legume system it was 9.7% versus 12.9% from the fertilizer-N system (Firth et al. 1974). In all the other comparisons of beef production listed above, we believe that the legume system would have been more profitable than the fertilizer-N one.

Busby and Van Beek's (1982) economic comparisons of systems of milk production in Qld showed that, for dryland tropical pastures, the legume-based system gave a slightly higher margin over feed costs than the fertilizer-N-grass system on a per cow basis, but the converse was recorded on a per ha basis.

With irrigated ryegrass and clovers, the legume system had the higher margins on both bases of comparison.

Apart from economics, convenience or risk factors, such as the risk of bloat on clover-based pastures, favour the use of fertilized grass rather than legumes.

Future Research Needs

There is a general research need for more adequate assessment of productivity of pastures in terms of livestock production. Herbage yield alone is inadequate since quality is highly important and stability, particularly of the legume, must be assessed. Too many grazing trials have not provided sufficient intensity of grazing to allow increased production to be measured in terms of animal performance.

Mediterranean and Temperate Legumes

Some of the current problems of forage legumes in southern Australia have external economic causes, but there is still much research and extension that can be done to maintain an input of N that has been of great value to the Australian economy. There is a particular need to develop annual legume cultivars that persist well under the new grain cropping systems and to convince graziers of the importance of managing their pastures to maintain adequate seed reserves. Further research on the problems of insect pests, plant diseases and soil acidity also warrants a high priority.

There is a continuing need for research to increase legume yields and adaptability, especially cool-season production. There is apparently little genetic variation for cool season growth (Collins et al. 1983) but there is ample scope for enhanced forage production through studies of seed yield and seedling establishment. There is a need for research to make more efficient use of the N that legumes fix. There is indirect evidence of large losses of legume N under grazing, e.g., 50% of the estimated fixed herbage N, a figure comparable with losses from fertilizer N (Simpson 1974).

Tropical Legumes

There are many challenges in tropical legume research. There are challenges in the legumes themselves--to find legumes that will withstand heavy grazing, to overcome important diseases such as anthracnose of stylos, and to find forage legumes that will form stable mixtures with grasses on the clay soils of the sub-tropics. There are systems problems--to find legume-based pasture systems that will be economic to develop and maintain even if beef prices remain low and to integrate sown pastures with agricultural crops (for example, through ley farming or legume intercropping systems) and with native pastures both in the sub-tropics and tropics.

Nitrogen-Fertilized Grass

There are two particular problems with N-fertilized grass--the feeding value of grasses is generally inferior to that of legumes, and the efficiency of use of the added fertilizer N may be even lower than it is for fixed N. Reports of 60%-80% loss from N applied to pastures (Catchpoole and Henzell 1975) indicate the importance of the problem, and this is an area worthy of further study. The present practice of applying the same rates of N to grassland year after year may well be a wasteful use of an expensive material. It assumes a negligibly small residual value of the fertilizer N, an assumption that does not appear to be borne out by the small amount of information that exists (Colman 1980). The residual value of fertilizer N requires further rigorous examination. Further work is also required into variations in seasonal productivity and soil chemical problems arising from long-term N usage.

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Discussion

Marten: I have two questions. 1. Of the total area under forage in Australia, what costs are involved to introduce legumes, that is, costs of using N on grass relative to the cost of introducing legumes, e.g., in Hawaii it is more economic to apply N? 2. What would be the costs of fertilizer N relative to legume nitrogen?

Clements: 1. Cost will vary from system to system. In the southern Australian wheat belt the cost is small, but where costs cannot be recovered from a cropping operation they are significant disincentives to pasture improvement. 2. Most N is used in strategic applications and not all year round. Cost of N/unit for fertilizer is 63¢ to $1.00/kg. Cost of N from legume-based pastures is probably less than 20¢/kg N.

Runge: Have you gone to urea N in Australia? What kind of losses do you get from applied urea?

Clements: About half of Australia's fertilizer nitrogen is applied as urea. Catchpoole and Henzell (1975) reported losses of 60-80% from urea applied to a pasture in southeast Queensland. Subsequently, Catchpoole et al. (Catchpoole, V.R., Oxenham, D.J., and Harper, L.A. 1983. Transformation and recovery of urea applied to a grass pasture in S.E. Queensland. Aust. J. Exp. & Anim. Husb. 23:80-86.) found losses averaged 29% during the 14 days after application, approximately half of which could not be accounted for by ammonia volatilization. Recovery of applied N in plant tops after 14 days ranged from 27% to 45% depending on the time of year.

Vallis: Losses of 60 to 80% are mentioned, with a 30% direct loss as ammonia. The remaining loss may be associated with the grazing animal and thus is not a direct loss from the fertilizer.

Syers: What is the validity of the claim that superphosphate applications reflect inputs of symbiotic N_2-fixation? The assumption may be questionable.

Clements: Agreed.

Helyar: What is the impact of stocking rate on N response?

Clements: N response is dependent on stocking rate, and the herbage yield response to N decreasing with increasing stocking rate.

Lancashire: What type or form of legume association with kikuyu grass have you assessed?

Clements: The legume to go with kikuyu may well be white clover as indicated at Kaikohe. Really, though, it is very difficult to say. The question is affected by climatic limitations, because the Australian "kikuyu zone" encompasses a range of microclimates, some of which are more suitable for white clover than others. Many legumes, both temperate and tropical, have been tested, and more needs to be done.

Barnes: Could you elaborate on the necessity for white clover breeding programs and those with particular emphasis on legume compatibility with grasses? Where should such programs be located?

Clements: White clover breeding inputs may well be best based in Victoria where current use is highest. However, there is potential for white clover in the subtropics, particularly for cool season production and as an annual with kikuyu pastures. White clover behaves rather differently in these two contrasting regions, and is associated with grasses of differing morphology and seasonality of growth. White clover is also a significant legume in the New England region of New South Wales and on irrigated farms along eastern inland river systems.

Productivity and Economics of Legume-Based Pastures and Grass Swards Receiving Fertiliser Nitrogen in New Zealand

P. Roger Ball and T.R.O. Field[1]

Abstract

Almost all intensively managed forage systems in New Zealand are legume based. Grass-clover pastures have a potential production in excess of 15 t DM/ha/yr in favourable areas. Soil water deficits cause most of the between-site and between-year variation in herbage production from well managed pastures. Little fertiliser nitrogen (N) is used, mostly in a tactical role.

Large inputs of fertiliser N have been investigated on developed grass-clover swards. Total yield is increased while clover yield and N fixation are reduced. Grazing management and fertiliser practices can modify the extent of clover suppression.

Around 300 to 600 kg of fertiliser N/ha/yr is required on pure grass swards to sustain forage yields similar to those from high producing grass-clover associations. Reliance on fertiliser N may allow moderate savings on other fertiliser nutrients.

The economic value to New Zealand of pasture legumes, both as forage and for N fixation, approaches NZ $2 billion/yr. There are indications that biologically-fixed N may be utilised more efficiently than fertiliser N for herbage production. Monetary costs, support energy requirements and social costs all militate against greater use of fertilisers for the N inputs required to sustain grassland farming in New Zealand. More research is required, particularly to establish the livestock production potential of grass swards receiving fertiliser N, under otherwise optimal management.

Introduction

Pastoral agriculture in New Zealand is based on grass-legume associations. High production levels are a heritage of large inputs of phosphatic fertilisers, which have encouraged introduced legumes and increased soil nitrogen (N) availability in farmed areas. Symbiotic fixation is relied on directly to provide the substantial inputs of N required to build and sustain soil fertility for intensive grassland farming and, indirectly, to meet much of the N requirement for periodic arable crops. Historically, fertiliser N inputs have remained low, averaging less than 5 kg/ha/yr. Walker (1969) went so far as to predict that there would be no dramatic rise in the use of fertiliser N on pastures, but a slow increase as farmers learnt to use it profitably. Ten years later, Field and Ball (1978) concluded, on the basis of both experimental and farm experience, that relatively small, tactical inputs of fertiliser N had an established role in the management of heavily-stocked farms.

A more intensive role for fertiliser N in N.Z. livestock farming was argued by Dr K.J. Mitchell in the late 1960's as a result of reduced costs for fertiliser N; down from about NZ$2.40 to $0.40/kg. Mitchell (1969) suggested that white clover formed the basis for extensive systems only, and that intensification required its "pensioning off" in favour of fertiliser N-based systems. His economic analyses suggested a 12% advantage in feed production costs from fertiliser N-based, permanent grass mixtures, when partly used *in situ*, and a 7% advantage when totally cut and stored. A system based on maize (*Zea mays* L.) and a winter annual grass indicated an almost 50% saving.

Elliot (1969) and others disagreed with this view. They suggested that fertiliser N had a fairly clear and limited role to play and, even at that time of low N prices, the economic advantages of a higher cost-higher output system were questionable. Nevertheless, Elliot (1969) suggested that more work on potential yields and necessary inputs should be carried out so that economics could be evaluated more stringently. Unfortunately, neither experimental nor practical farm data required to perform this analysis have been collected in the interim.

In this contribution, then, we have collected together available data on productivity of legume-based and fertiliser N-based pastoral systems in New Zealand, and have tentatively compared these alternative strategies for intensive livestock production.

Legume-Based Systems

Considerable diversity exists throughout N.Z. grasslands, with respect to botanical composition of swards, fertiliser and lime practices, and grazing management (Levy 1970; Sheath and Harris, this Proceedings). This paper focuses on productive, intensively managed grasslands, most of which occur on about 4.5 million ha of flat and downland. They are confined to areas where the climate allows a long growth season and where soils are fertile or made so by appropriate management. Ryegrass (*Lolium* spp.) and white clover (*Trifolium repens* L.) are the mainstay species, but other grasses, legumes and herbs almost always make a minor contribution. Other species would normally dominate only in special-purpose swards containing, for instance, lucerne (*Medicago sativa* L.), prairie grass (*Bromus cartharticus* L.) or red clover (*T. pratense* L.). An important exception to this generality is the substantial contribution made to forage production by paspalum (*Paspalum dilatatum* Poir.) and Kikuyu grass (*Pennisetum clandestinum* Hochst. ex Chiov.) in some pastures in warmer regions of the North Island.

The ecology and management of white clover-based pastures has been considered in detail elsewhere (Sears 1962, Brougham et al. 1978). It is sufficient here to note that clovers are weaker competitors than associated grasses for nutrients

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other than N, which are likely to limit pasture growth. Cultivation and sward renewal provide a means by which clover performance, both yield and N fixation, may be greatly enhanced, but this option is not widely pursued.

Potential Productivity

Potential production from pastoral systems in New Zealand is described in figure 1. Isoquants were derived from potential stock carrying capacities (PSCC) annotated in the N.Z. Land Resource Inventory (Blashke et al. 1981). Of the 6 million ha of pasture in the North Island (total area 11.4 million ha) 23% is classified as having a high PSCC, which, by cross referencing to measured pasture production, would comprise lowland swards yielding from 10 to 20 t dry herbage (DM)/ha annually. The medium and low production areas, which constitute 67% and 10% respectively, are generally more than 200 m above sea level and are based on varying mixtures of unimproved and improved pasture yielding 7 to 10 t and 5 to 7 t DM/ha annually.

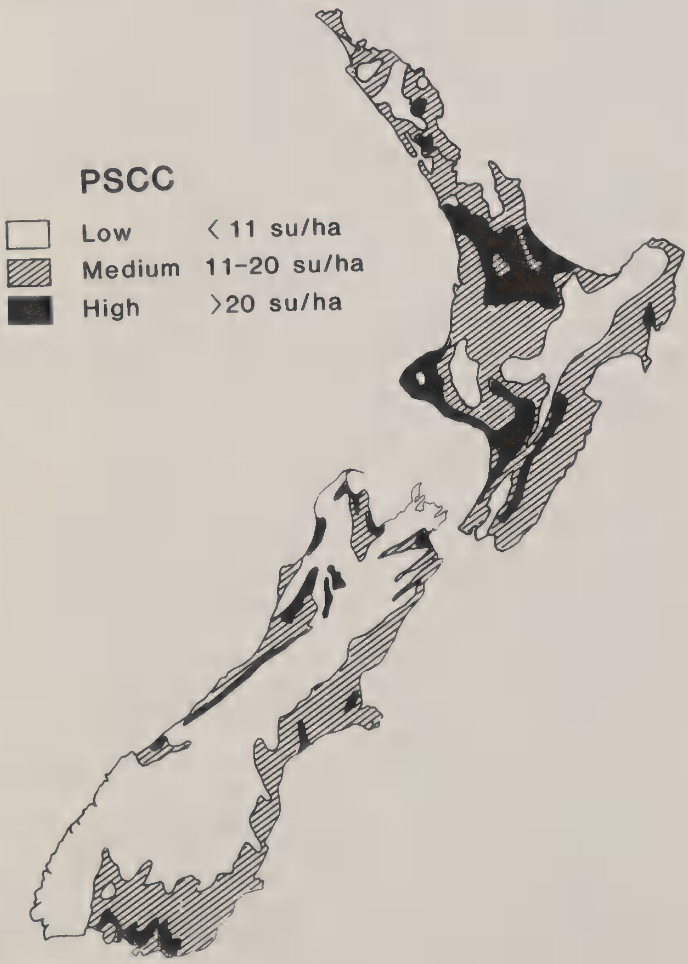

Figure 1--Potential stock carrying capacity (PSCC, in stock units (su)) of the North and South Islands of New Zealand.

In the South Island (15.1 million ha) the total area of grazing land is nearly 9 million ha. However, there is less than 0.5 million ha (7%) of improved pastures with a high PSCC, restricted to Southland, Westland and isolated pockets of alluvial downland. Most of the remainder (56% of South Island grazing land) falls in the low PSCC classification and comprises tussock- or scrub-grassland associations.

Farming Systems and Environmental Constraints

Within these production zones, the seasonal pattern of herbage production determines the type of pastoral enterprise pursued. Grassland farming is generally based on reproductive ruminants, both sheep and cattle. Mating is timed to provide offspring around late winter-early spring, so that feed requirements are matched as closely as possible with forage supply. Virtually all grassland is grazed and few animals are housed. Typically, productive grasslands are rotationally grazed year round, swards are relatively permanent and little forage conservation occurs. Even on the most intensively managed dairyfarms no more than 10% to 15% of feed requirements are met with silage or hay (Hutton and Bryant 1976). Supplements, or concentrate rations, are not normally fed at all, and inputs of support energy in the form of machinery and agricultural chemicals are small compared with intensively managed farms in North America and Northwest Europe.

Year-to-year variation in herbage production, caused by weather vagaries or insect pests, limits further intensification of grassland farming. Decisions must be made in advance on stocking rate and animal reproduction dates, leaving little scope for managers to cope with large fluctuations from one year to another. Baars (1982) found that year-to-year variation in herbage production from well managed lowland sites throughout the North Island amounted to between 10% and 50% of the 5-year mean. Largest differences in herbage accumulation rate, both within and between sites, occurred in the summer-autumn period, reflecting site differences in both the water-holding capacity of soils and in rainfall. Herbage accumulation displayed much less variation during late winter and spring, and was highly correlated (r^2=0.91) with accumulated day-degrees above 6°C (10 cm soil temperature), itself strongly correlated with solar radiation.

A 2-year study at 9 lowland sites throughout New Zealand (Hoglund et al. 1979) also examined year-to-year variation in production from mixed swards rotationally grazed by sheep. In the wetter year, white clover yield was nearly double that measured in the dry year, while grass yield was little affected. Among sites, yearly white clover yield, but not grass, was strongly correlated with water stress-free degree-days. Of numerous weather statistics tested, mean air temperature had a positive influence on N fixation by white clover in winter and a negative influence in summer. However, stress-free degree-days showed a correlation with N fixation only when a 15-day lag period was introduced.

Legume-Based Systems With Fertiliser Nitrogen

Interest in using fertiliser N on N.Z. grasslands persists for three main reasons:

(i) The reliability of pasture growth rates during late winter and early spring may be improved by use

of fertiliser N over this period (During 1972, Lazenby 1983). Fertiliser N can help offset slow growth, when this reflects adverse conditions for soil N mineralisation rather than limitations to plant growth in the aerial environment.

(ii) The highly seasonal nature of pastoral production requires substantial capital investment to process peak product flow. Processors in both the meat and dairy sectors are contemplating payment systems that will encourage a wider-based pattern of production (Taylor 1982).

(iii) Intensification of grassland farming has reduced the margin between forage availability and animal requirements. Fertiliser N can increase forage production.

Fertiliser N can be applied to grass-legume swards on either a tactical or continual basis. Relatively small, tactical inputs have most relevance to the first two strategies listed above. However, to increase significantly the quantity of forage produced on a year-round basis, continual inputs of fertiliser N are required.

Tactical Inputs of Fertiliser N

Responses following tactical application are only transient, with DM and species composition changes generally only measurable for a matter of 2 to 6 months. However, these applications have become an important management tool in dairyfarming and in grass seed production from mixed swards (Ball and Field 1982). Between 10 and 20 thousand tonnes of fertiliser N have been applied to N.Z. pastures each year over the last decade, mostly in tactical applications which seldom exceed 50 kg N/ha, with no more than two applications to a pasture in any one year.

Continual Inputs of Fertiliser N

Continual application of fertiliser N to grass-legume swards has only been carried out on an experimental basis, and then only in a limited number of studies. Those discussed in the following section were carried out in Waikato (Weeda 1964), Manawatu (R.W. Brougham and P.R Ball, unpublished data; Ball 1979; Harris and Hoglund 1980) and Southland (Harris et al. 1973).

Application of fertiliser N to a grass-clover sward, whether on a tactical or continuing basis, in almost all cases leads to increased yield from the non-legume components of the sward. Greater grass production from repeated applications through the year is usually matched by a decline in the annual productivity of clovers. This interrelationship between grass and clover production at various levels of fertiliser N is shown in figure 2. The solid line indicates the upper bound for a large number of results from trials conducted in The Netherlands, and summarised by Ennik (1982). Only in the cutting trial of Weeda (1964), in which cocksfoot was the associated grass, did N.Z. results resemble European data. In all the other grazing trials, control (no N) legume and grass yields were much greater and clover yield appears to have been less affected by increased production from the fertiliser-stimulated grasses.

Measured total production from control swards in the N.Z. grazing trials (fig. 2) varied from 13.4 to 17 t DM/ha/yr. At the highest levels of N applied, annual yields were increased by 3.8 t (with 450 kg N/ha) and 3.6 t DM (800 kg N/ha). Other results involving continual N applications under grazing (Holmes and Wheeler 1973, O'Connor and Cumberland 1973), which are not plotted in the figure because of the absence of botanical composition data, fall into this production range.

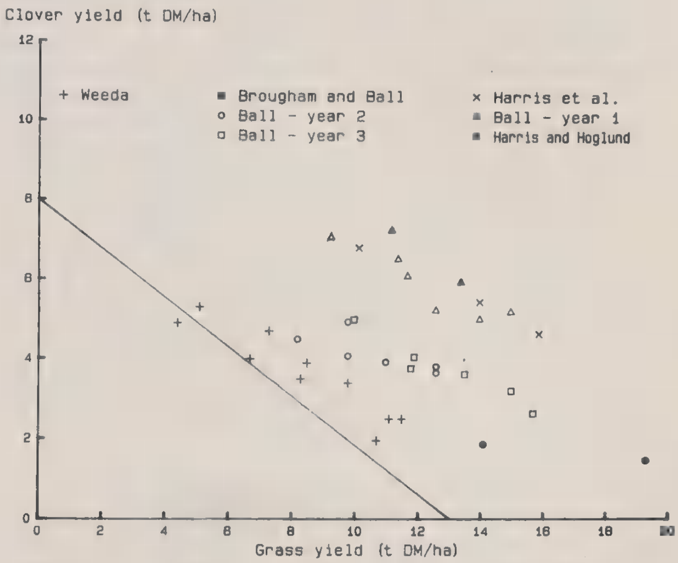

Figure 2--Clover and grass annual dry matter production (t DM/ha) from grazing experiments with at least 2 levels of fertiliser N application. The line is the upper bound of data reviewed by Ennik (1982).

An increase of 3 t in grass production led to a decline of 1 t in clover yield, on average, in the N.Z. grazing trials. By contrast, in the most productive cases examined by Ennik (1982), an increase of only 1.75 t of grass displaced 1 t of clover. The greater stability of clover production in New Zealand probably arises from less overlap of the period of grass responsiveness to N and the period when most legume growth occurs. Fertiliser N responses generally occur from late autumn to early summer (Field and Ball 1978, Ball and Field 1982), while the major period for white clover growth in the presence of a companion grass extends from late spring to late autumn (Harris and Hoglund 1980). The resemblance of Weeda's (1964) results to European data supports this view, as cocksfoot is a summer-active grass and would respond to fertiliser N during the main period of clover activity.

Trends in annual N yields from the components of grass-legume swards further highlight the difference between Northwest European and N.Z. data. Whereas British data quoted by Ennik (1982) showed a straight substitution of grass herbage N for clover herbage N in response to N dressings (solid line,

fig. 3), there was only a partial substitution indicated in data from Ball (1979, see fig. 3). In a high production year (year 1), when there was

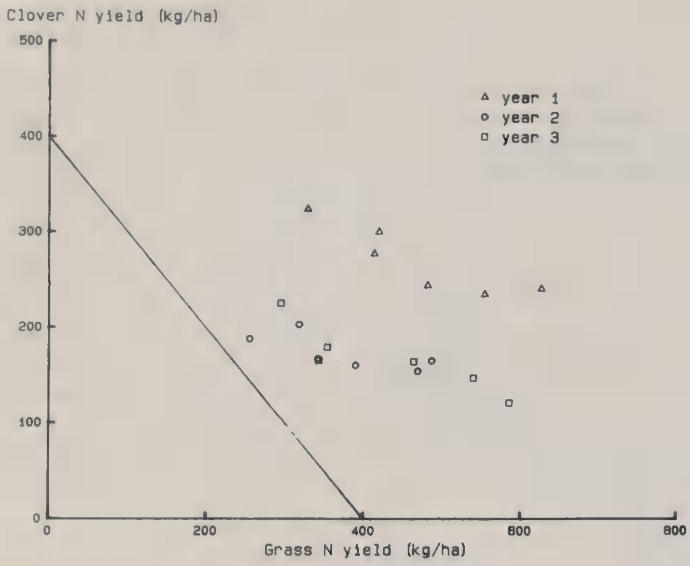

Figure 3--Clover and grass annual N yields (kg N/ha) from 3 years of Ball's (1979) grazing trial with 6 levels (0 to 450 kg N/ha/yr) of fertiliser N application.

little restriction by soil water deficit on growth and N fixation, the increase in clover N yield from unfertilised swards, over that of the drier years, was nearly twice that of grass N yield. The response in clover and grass N yields to fertiliser N input was similar in all sets of growing conditions.

In the final year monitored by Ball (1979), N fixation by clovers was reduced proportionately more at high fertiliser N levels than clover N yield. Acetylene reduction assay indicated total fixation of 53 kg/ha with 450 kg/ha fertiliser N added, compared with 263 in ryegrass-clover controls and 10 in a pure grass sward. If we assume that clover herbage N yield represents 45% of total N incorporated by white clover (P.R. Ball, unpublished data), then there appears to have been a direct substitution of soil and fertiliser N for 76% of clover requirements in the 450 kg N/ha treatment, compared with a contribution from soil mineral N of 40% in control swards. Similarly, Crush et al. (1982) reported that application of 100 to 150 kg fertiliser N/ha/yr to cattle-grazed pasture in Manawatu reduced annual fixation by 30%, but clover yield by only 8% to 17%.

Minimising the Suppression of Clovers

Pasture management, through manipulation of grazing interval and fertiliser practice, can modify the effect of fertiliser N on grass-clover swards, although these influences have not been well defined (Ball and Field 1982). A long regrowth interval in spring or early summer, especially during forage conservation, can result in clover suppression. Where N is used, the more rapid grass accumulation rates and resulting higher yields can compound this effect. Further, nutrient deficiencies can lead to greater clover suppression. Experience in New Zealand suggests that as long as P, S and Mo levels are sufficient to maintain an active legume component in mixed swards, deficiency should not exacerbate clover suppression during and following N use (Lynch 1953, Ball and Field 1982).

Soil K level, on the other hand, may have to be elevated to safeguard clover performance with N use. Richards (1976) described two distinct N response patterns for mixed swards in the United Kingdom. More commonly, increasing grass N yield substituted directly for clover N yield, with little increase in total herbage N yield until the sward became distinctly grass dominant. Under such conditions clover N and fertiliser N were considered incompatible. Results from studies on soils with higher available K levels showed a more successful combination between clover and fertiliser N. Clover suppression was much less severe, so crude protein response was nearly linear over the full range of fertiliser N rates examined. This modifying effect of K was reported by Blaser and Brady as long ago as 1950. Their results were interpreted as showing that grass, with a greater K uptake at low temperature, had exhausted most of the limited K supply before clover growth commenced.

Likely to be most damaging to clovers in a mixed sward would be a combination of long regrowth interval with deficiency of some nutrient(s), even moderate deficiency of K, in association with fertiliser N use.

Grass Swards Receiving Fertiliser Nitrogen

Production data from four experiments involving N-fertilised ryegrass are listed in table 1. Control (No N) yields ranged from very low on an infertile subsoil (Sears et al. 1965) to the high value of 16.5 t DM/ha/yr (Harris and Hoglund 1980) on a fertile silt loam. Nitrogen responses were greatest where control yield was most restricted by N supply. The large response measured by Hunt and Mortimer (1982) also included a response to irrigation. Their data is the mean from two cultivars, with 'Grasslands Nui' perennial ryegrass yielding almost 30 t DM/ha/yr in small plots measured to ground level.

Yield from grass swards with large N inputs fell within the range or were greater than the expected yield from grass-legume mixtures at these sites. Where a direct comparison between mixtures and grasses was made under irrigation, Weeda (1964) found that more than 600 kg of fertiliser N/ha/yr was required for pure grass to yield at a level similar to grass-clover.

Economic Considerations

No significant move away from legume-based grassland farming to systems dependent on continual N dressings seems likely in the foreseeable future. Indications are that some 300 to 600 kg fertiliser N/ha/yr would be needed on pure grass swards to sustain the level of forage production currently attainable from well managed grass-clover associations, sustained by an annual input of 150 to

300 kg fixed N/ha (Hoglund et al. 1979, Field and Ball 1982). At present costs, the annual bill for applied N would be in the vicinity of NZ$300 to $600/ha. Even if applied N led to sustainable savings of 300 kg/ha of potassic superphosphate (N:P:K:S=0:6:16:7), this would only displace some $55/ha of the annual N cost at present.

Grass cultivars have not been specially bred in New Zealand for use with fertiliser N, nor have optimal management practices been defined for their culture. So the comparative potential of N-fertilised grass swards and N-fertilised grass-clover associations for livestock production has not been as fully evaluated as in parts of Europe and North America. Meanwhile it seems that the practice of supporting pure grass swards with fertiliser N will remain confined to grass seed production and occasional leys between arable crops.

Economic Value of Forage Legumes

The economic value of legumes to New Zealand as forage producers can be indirectly estimated from the value of gross agricultural production, which in 1981 totalled $4.07 billion (N.Z. Yearbook 1983). Allowance for the non-pastoral sector gives a value of approx. $3.5 billion for pastoral products that year. Assuming that legumes contributed 20% of the nutritional value of all forages consumed, then the monetary value of legume forages was around $700 million. On a N fixation basis, direct substitution with fertiliser N for the estimated 1 million t N/yr fixed by forage legumes provides an estimated worth for legumes of $1 billion. Lancashire (1983) independently estimated the combined worth of forage legumes as approaching NZ$2 billion.

The relative value of legumes for forage and N fixation changes with economic circumstances. Their forage contribution was of considerably greater value than their N input 15 years ago, when the fertiliser cost was less than one quarter that at present (Ball 1970).

Efficiency of Herbage Responses to Fertiliser and Fixed N

Estimates for the annual input of fertiliser N required on a grass sward to sustain DM yields at levels similar to productive, clover-based swards are virtually double present estimates for symbiotic fixation. This raises the question of whether the organic incorporation of N fixed by legumes results in better utilisation of the N input. Inorganic fertilisers are certainly more immediately at risk of loss through volatilisation, leaching and denitrification, on introduction to the soil-plant complex. Efficiencies for use of fertiliser N under appropriate conditions in this environment are generally in the range of 12 to 20 kg DM/kg N applied (Ball and Field 1982). Two estimates for efficiency of response to inputs of symbiotically-fixed N fall within this range (table 2), and two are very much higher. Experimental conditions may have influenced individual results. However, we consider that further investigation of this topic would be more fruitful than any attempt at a more detailed analysis of differences among these experiments.

Energy Requirements

The energy input required to produce traditional animal products from legume-based pastoral systems in New Zealand is very small. For example, Walker (1972) calculated that sheepfarming has an output of 30 (low production) to 100 (high production) MJ of pasture ME for every MJ of input energy, most of it as fuel. Similarly, White et al. (1982) calculated from British data that 35 MJ in ryegrass-white clover forage required the consumption of 1 MJ of support energy. By contrast, their calculations for perennial ryegrass forage receiving fertiliser N

Table 1 - Ryegrass monoculture responses to fertiliser N

Source and type	Yields (t DM/ha/yr) No N	+N	Input (kg N/ha/yr)[1]	
Sears et al. (1965), - herbage cut and removed	1.94	11.0	610	....
Weeda (1964), - cut and removed	6.08	13.2	900	(12)
Karlovsky (1964), - grazed	13.8	16.4	820	(6)
Harris and Hoglund (1980), - grazed + full return	16.5	17.6	180	(9)
Hunt and Mortimer (1982), - grazed with little return	11.5	24.4	2,150	(50)

[1]Number of applications in brackets.

Table 2 - Efficiency of pasture responses to inputs of symbiotic N

Source	Type	Yield (t DM/ha)	N fixation (kg N/ha)	Efficiency (kg DM/kg N)
Sears et al. (1965)	Cut grass, no added N, clippings removed	1.94	10	
7 years' data	Cut grass-clover, clippings removed	12.7	683	16.0
	Cut grass-clover, clippings returned	14.5	409	32.0
Ball (1979)	Cut and grazed grass, no added N	10.4	10	
3 years' data	Cut and grazed grass-clover	15.6	348	15.5
Lambert et al. (1982)	Grazed grass-clover moderate P, S stress	4.71	74	
1 year's data	Grazed grass-clover, adequate P, S	7.38	135	43.8

indicated an output:input ratio of only 3.3, with 97% of the total input energy required for fertiliser. White et al. (1982) assumed 10.2 t of forage DM fed after application of 430 kg N/ha/yr. Higher levels of production from grass swards receiving fertiliser N in New Zealand could, at most, double this ratio. Obviously, a legume-based system will remain far more energy efficient, even under the maximum levels of grass production that might be envisaged.

Social Costs

There is convincing evidence that intensification of traditional grassland farming in New Zealand has increased N leakage to the environment, principally by leaching and volatilization (Ball and Keeney 1983, see also papers in Gandar 1982).

Experimentation in the field (Steele and Shannon 1982) and with a model for N relationships (Field and Ball 1982) both indicated that use of fertiliser N in intensively managed grass-clover systems further increases the extent of N wastage. A recent field study in the United Kingdom (J.C. Ryden, P.R. Ball and E.A. Garwood, unpublished data) revealed that while some 30 kg nitrate-N/ha/yr was leached below a ryegrass-white clover sward grazed by cattle, the leaching loss was five-fold greater below a grazed ryegrass sward receiving 420 kg N/ha/yr as ammonium nitrate.

Research Needs

The following topics, not necessarily in priority order, require further research in New Zealand. (Topics 1 and 2 must eventually be assessed in terms of livestock production.)

1. Response patterns and potential production from grass swards receiving fertiliser N warrant further attention. Optimal management for individual species requires definition.

2. For grass swards, the quantity of fertiliser N required to sustain yields similar to those attainable from grass-clover mixtures requires assessment. This research should span the range of environments from intensively managed lowland through to more extensive systems.

3. Greater efficiency of utilisation of symbiotically-fixed N is indicated by our preliminary calculations. Further research could provide improved understanding of the processes involved and lead to better utilisation of fertiliser N.

4. Better definition of reactions by grass-clover swards to a range of fertiliser N inputs is required.

5. Our understanding of N leakage to the environment from grass-clover pastures, while improving, is still limited. No N.Z. information is available for grass swards receiving fertiliser N. Further research may indicate important differences for the protection of fragile environments.

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Discussion

Lancashire: From the farming press, it appears that there are large and profitable returns from applying fertilizer N in New Zealand. You do not seem to have painted this picture in your paper.

Ball: In grass-clover swards, financial gains can be made by tactical applications of N. There is a place for increased N use on mixed pastures. We see no likelihood of a move towards pure grass swards sustained by fertilizer N.

Stern: What is the lowest figure for percentage of clover in N-fertilised lowland pastures? There is wide variation in efficiencies of response to symbiotically fixed N. Would you speculate why?

Ball: The lowest clover content on an annual basis is about 10%. It is difficult to provide a full explanation. Both these preliminary results and the observation that it seems to take twice as much fertilizer N as symbiotically fixed N to obtain the same herbage yield, indicate that more research is needed in this area.

Heichel: You summarized the virtues of using fertilizer N. What is the net financial return to high inputs of fertilizer N?

Ball: Economic returns for the alternative systems are difficult to provide, because so little information exists about N application to pure grass swards. It is difficult to extrapolate from grass-clover mixtures as N responses may differ.

Steele: All N.Z. pastures are N-deficient. We should be looking at the profitability of N applied to mixed, not pure swards. One can expect an overall increase of 30% DM by applying N to a mixed sward.

Ball: Our results concur with your observation. The annual yield from a well managed grass-clover pasture is increased by 25% to 35% by providing nonlimiting N. Overseas information indicates that fertilizer N responses obtained from short-growing species, like ryegrass and white clover, should be better from a mixture than from monocultures.

Brougham: There is a need for research in two areas: fertilizer N applications to mixed swards; and enhancement of the efficiency of N-fixation by forage legumes, perhaps through genetic engineering. Which horse would you back?

Ball: Neither approach seems exclusive of the other. Preferably, we need to continue research in both areas to enable us to make valid comparisons.

Knight: What is the source of fertilizer N in experiments? Was soil pH monitored?

Ball: Various sources of fertilizer N were used in different experiments. Yes, soil pH was monitored.

Minson: What was the basis of your assumption that 20% of animal production was derived from legumes?

Ball: The following assumptions were made: (a) About two-thirds of the value of pastoral products arise fom lowland and downland, for which available information suggests a 20% legume contribution to yield. No adjustment was made for differences in forage quality. (b) While available information would indicate a lower legume content for most hill and high country pastures, an element of selective grazing probably enhances the contribution of legumes to animal diet.

Productivity and Economics of Legume-Based vs. Nitrogen-Fertilized Grass-Based Pasture in the United States

J.C. Burns and J.E. Standaert[1]

Abstract

Productivity of pastures in the United States can be appreciably increased through nitrogen fertilization. An alternative means of increasing both the pasture yield and quality is through the inclusion of a legume at seeding or by sod-seeding legumes into established grasses. In 24 experiments conducted in the United States, steer daily gains from legume-grass were 0.14 kg day^{-1} more than from nitrogen-topdressed grass. An increase in favor of legume-grass of 0.15 kg day^{-1} was obtained for calves when cow-calf units were grazed (seven experiments). Steer gain ha^{-1} averaged 385 kg from legume-grass pastures. Of the legumes studied in mixture, white clover provided highest gains of 435 kg ha^{-1}. Different legumes in combination with grass showed different yield potentials. To enable comparable steer gain ha^{-1} to that from white clover-grass, birdsfoot trefoil-grass, and alfalfa-grass, pure grass stands required nitrogen applications of 200 kg, 170 kg, and 270 kg, respectively. Generally, 200 kg of N ha^{-1} was required for grass to produce the approximate 400 kg ha^{-1} expected from legume-grass mixtures. The substitution of legume N for fertilizer N in forage dry matter production and the management factors to consider in choosing legume-based or N-grass systems with regard to economic implications are considered. An economic assessment was made comparing a ladino clover (*Trifolium repens* L.) tall fescue (*Festuca arundinacea* L.) mixture with nitrogen topdressed tall fescue at equal ha^{-1} productivity, with legume persistence given economic consideration.

Introduction

The decision to use legume-based or nitrogen- (N-) fertilized grass pastures is extremely difficult. Many factors such as the soil, the plant, and the animal must be given simultaneous consideration. The short-lived nature of perennial legume stands in mixtures is probably the most serious limitation to legume-grass mixtures. Managers must adopt management practices that help retain legumes grown in mixture with aggressive perennial grasses. Also, animal management for efficient use of forage and general animal health must be given consideration (Van Keuren and Hoveland 1984). Although biological factors are important, careful consideration must be given to production economics and to marketing opportunities (Jacobs and Striker 1978) and social factors. In some areas of the United States, the beef cow enterprise is small and a segment of a diversified operation or consists of a part-time farming commitment which may not demand high inputs of management and technology. Further, today's markets are highly volatile for long-term animal enterprises.

Winter feeding of stored forages across 85% or more of the United States adds a complication to evaluating forage systems, because many feed sources are available and used to assure year-round feeding. Yet a 6- to 10-month grazing season provides a significant opportunity to alter production efficiency on pasture. The dry matter productivity and animal responses from legume-based compared with N-fertilized pastures and some economic implications are discussed. Major consideration is given to temperate perennial forage species which constitute the components of most legume-grass mixtures grown in the United States.

Biological Considerations

The major seeded and cultivated perennial forage grasses and legumes used in mixture in the United States are listed in table 1 (note abbreviations for each species). Most of these species can be found from eastern Nebraska to the east coast and at higher elevations in the west. Water is frequently the first factor limiting their occurrence in the West.

In the Deep South, from mid-Texas east, annual legumes provide an important source for winter grazing either alone or in combination with annual grasses. Overseeding of subtropical perennial sods is frequently practiced. The use of tropical legumes in mixture with grasses is primarily restricted to below south-central Florida.

Daily Animal Responses

Daily animal gains are of major importance in the beef industry because animals are sold based on weight and body condition. Light cattle generally bring less return $animal^{-1}$ even though selling price $unit^{-1}$ weight generally increases with decreasing weight. This differential is altered by body condition represented by a grade placed on the animal when marketed. In the less frequent situations of grazing lactating dairy cows, the response of interest is 4% fat-corrected milk (FCM) $animal^{-1}$ day^{-1}.

A comparison of daily performances for steers and calves from studies that involved legume-grass and N-fertilized grass comparisons throughout the United States provides insight into the merits of these pasture systems. Before examination of these data, it is important to consider the validity of such general comparisons from unrelated studies. Data from irrigated and nonirrigated experiments where animals were differentially wintered show several important points (table 2). Animals wintered to gain 0.16 kg day^{-1} gained more when later grazed on irrigated pastures of both OG and TF than animals wintered to gain 0.59 kg day^{-1} (Heinemann and Van Keuren 1957). Regardless of winter feeding regime and grass species grown in the legume-grass mixture, subsequent animal summer daily gains were consistently

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Table 1 - Major grasses and legumes used in mixtures in the United States

Grasses		Legumes	
Code	Name	Code	Name
BH	Bahiagrass (Paspalum notatum Flugge)	AC[1]	Annual clovers (Trifolium sp.)
BG[1]	Smooth bromegrass (Bromus inermis Leyss.)	AA[2]	American jointvetch (Aeschynomene americana L.)
BD	Bermudagrass [Cynodon dactylon (L.) Pers.]	Al[1]	Alfalfa (Medicago sativa L.)
CG[3]	Carpetgrass (Axonopus affinis Chase)	BV	Bigflower vetch (Vicia grandiflora Scop.)
DG	Digitgrass (Digitaria decumbens Stent.)	BT	Birdsfoot trefoil (Lotus corniculatus L.)
IW[1]	Wheatgrass [Agropyron intermedium (Host) Beauv.]	CM	Cicer milkvetch (Astragalus cicer L.)
KG[1]	Kentucky bluegrass (Poa pratensis L.)	DI[2]	[Desmodium intortum (Mill) Urb]
NP	Native pasture	DH[2]	[Desmodium heterocarpen (Linn) DC]
OG[1]	Orchardgrass (Dactylis glomerata L.)	HV[1]	Hairy vetch (Vicia villosa Roth)
RG	Reed canarygrass (Phalaris arundinacea L.)	LP	Lespedeza [Lespedeza cuneata (Dumont) G. Don or striata (Thumb) H and A]
TF[1]	Tall fescue (Festuca arundinacea Schreb.)		
TM[1]	Timothy (Phleum pratense L.)	RC	Red clover (Trifolium pratense L.)
		SC	Subterranean clover (T. subterraneum L.)
		WC[1]	White Clover (Trifolium repens L.)

[1]Most widely used.

[2]Limited use outside of Florida.

[3]Widespread in South, but not productive.

Table 2 - Relative animal responses from pastures following winter feeding at two nutrition levels resulting in low and high winter average daily gains (ADG)

Winter nutrition		Subsequent summer responses					
Level	Avg. gain (kg day^{-1})						
A. Irrigated pastures[1]		Orchardgrass (kg day^{-1})			Tall fescue (kg/day^{-1})		
		224N[2]	Alfalfa	Clover	224N[2]	Alfalfa	Clover
Low	0.16	0.87	1.07	1.29	1.08	1.15	1.21
High	0.59	0.70	0.76	1.08	0.63	0.95	1.03
B. Nonirrigated pastures[3]		Kentucky bluegrass (kg ha^{-1})					
		133N[2]	Legume mix				
Low	0.39	378	400				
High	0.99	230	272				

[1]From Heinemann and Van Keuren 1957.

[2]kg ha^{-1}.

[3]From Mott et al. 1952.

highest from WC-grass, followed by Al-grass, with lowest gains on N-fertilized grass.

For nonirrigated conditions (assuming comparable grazing periods), animal gains (kg) ha^{-1} reflect the same response as noted for daily gains above with the higher seasonal ha^{-1} productivity from animals that were wintered to gain 0.39 kg day^{-1} compared with those wintered to gain 0.99 kg day^{-1} (table 2). Also, gain ha^{-1} from pasture treatments were ranked similarly regardless of animal condition at the time grazing was initiated (Mott et al. 1952). Consequently, reasonable confidence can be placed in generalizations from a number of independently conducted trials that compare legume-grass mixtures with pure grass topdressed with N. Data from 38 different experiments are presented in table 3. The N application rates and animal responses to each grass in pure stand are shown in the left portion of the table. The data from the legume-grass mixture using the same grass are given in the right-hand portion of the table. When several legumes have been compared with the same N-topdressed grass, they are listed in the same column.

It is clear that legume-grass mixtures consistently resulted in higher daily gains for both steers and calves than did pure grass stands. The only exception is item 21 (KG-112N vs. KG+BT) where daily gains were equal (0.51 kg). Steers on the legume-grass mixtures gained an average of 0.14 kg day^{-1} more than steers on pure grass. A similar value of 0.15 kg day^{-1} was obtained for calves. This difference reflects the high quality of the legume-grass mixture and can be attributed mainly to higher digestibility and greater daily intake (Templeton 1978). The greater performance from the mixture would net an increase in live weight of 27 (0.145 kg x 186 days) to 32 kg $animal^{-1}$ for a 6-to-7 month grazing season.

Although legumes increased daily animal performance, the companion grass species in the mixture may also influence gains. Steer daily gains (table 3) from TF and OG grown in combination with a legume, were consistently different in favor of OG. The average difference from 13 experiments favored OG by 0.11 kg $animal^{-1}$ day^{-1}. Explanations for the reduced performance from TF may reside in (1) the recent isolation of a fungal endophyte and its negative role in animal function (Hoveland et al. 1983), or in (2) the invariably lower legume percentage found in legume-tall fescue mixtures due to the competitive nature of tall fescue compared with orchardgrass. The general absence of botanical data (given for 13 of the 38 studies, table 3) from legume-grass treatments in grazing trials is a major weakness in much of the literature. Frequently, legume-grass treatments that were initiated with an adequate legume component of a mixture retain their treatment designation when published even though the legume component may be nearly lost at termination of a 3- to 5-year trial.

From the limited data shown for lactating dairy cattle (table 3) production $animal^{-1}$ was in favor of the legume-grass mixture (items 34, 35, 37, and 38) with a WC-OG mixture generally yielding more FCM day^{-1} than other mixtures (item 32 is an exception).

Table 3 - Average daily response for beef and dairy cattle and response hectare^{-1} from N-topdressed grass and grass-legume mixtures[1]

		Nitrogen (kg ha^{-1})		Pure grass and animal response					Legume in mixture and animal response						
				Grass	Daily (kg)			Product	Legume		Daily (kg)			Product	
Item	State	Grass	Mixture	species	Steer	Cow	Calf	(kg ha^{-1})	Species	%	Steer	Cow	Calf	(kg ha^{-1})	References
Beef cattle weight gains:															
1.	Fla.	34		CG	0.35			166	LP		0.44			245	Blaser et al. 1948
									WC		.42			694	
2.	Fla.		39		.79				WC		.80				Warnick et al. 1965
3.	Fla.	112		BH	.27			253	AA		.34			259	Hodges et al. 1976
4.	Ala.	224		TF	.97			476	BT		1.07			377	Hoveland et al. 1982
				OG					BT		1.33			400	
5.	Ala.			NP			0.63	100	NP				0.84	169	Cope et al. 1973
			112	NP			.79	163	NP				.86	210	
6.	Ala.	168		TF	.48			419	WC	24	.69			652	Hoveland et al. 1981
									BT	13	.69			446	
7.	Ala.	168		TF	.59			300	WC		.66			273	Harris et al. 1972
		168		OG	.80			224	WC		.83			273	
				BD					HV		.59			553	
8.	Ala.	112		BD	.81			363	LP		.71			271	Hoveland et al. 1969
		168		BD	.67			368							
9.	Ala.	112		BD		0.22	.71	511	AC			0.62	.89	785	Hoveland et al. 1978
10.	Miss.	134		BD	.44			316	WC		.64			579	Hogg 1965
									RC		.39			231	
11.	S.C.	168		TF	.46				WC		.47				Jutras et al. 1978
				OG	.42				WC		.58				
12.	N.C.			TF					WC		.92			395	Gross et al. 1966
				OG					WC		.83			384	
				OG					Al,WC		.73			338	
		224		TF+BD	.50			486							
13.	N.C.	252		KG	.46			345	WC		.56			211	Burns et al. 1970
14.	N.C.	185		TF		.15	.58		WC	20+		.31	.76		Goode et al. 1972
15.	N.C.	224		KG		.37	.76	334	WC	20		.44	.84	245	Burns et al. 1983

Table 3 - Average daily response for beef and dairy cattle and response hectare^{-1} from N-topdressed grass and grass-legume mixtures[1]—Continued

		Nitrogen (kg ha^{-1})		Pure grass and animal response					Legume in mixture and animal response						
				Grass	Daily (kg)			Product	Legume		Daily (kg)			Product	
Item	State	Grass	Mixture	species	Steer	Cow	Calf	(kg ha^{-1})	Species	%	Steer	Cow	Calf	(kg ha^{-1})	References
16.	Va.	242		TF	0.38			484	WC		0.44			444	Blaser et al. 1956
		242		OG	.38			400	WC		.49			418	
17.	Va.	224		TF	.41			411	WC		.46			346	Blaser et al. 1969
		224		OG	.49			373	WC		.58			369	
18.	Tenn.	187		TF	.48				WC	37	.56				High et al. 1965
19.	Tenn.			TF					WC	33		.39	.87		Anderson and Safley
				OG					WC	24		.29	.86		1967
20.	Ohio		67	NP	.47			251	BT		.68			363	Davis and Klosterman 1959
21.	Ind.			KG	.48			220	BT		.51			382	McVey and Mott 1956
		134		KG	.51			343							
22.	Ind.	112		TF		.01	.58		NP			.26	.83		Petritz et al. 1980
23.	Iowa		67	NP	.55			250	BT		.76			423	Wedin et al. 1967
			67	NP		.28	.77	184	BT			.44	.87	178	
24.	Iowa		134	NP	.74			421	Al		.80			434	Wedin 1965
25.	Mich.		57	OG	.69			276	WC		.83			326	Ried and Greathouse
				RG	.70			279	Al		.82			324	1974
26.	Nebr.[2]		280	OG,BG	.88			965	Al(168N)		.90			987	Nichols et al. 1982
									CM(168N)		.93			908	
									Al		.87			709	
									CM		.73			563	
27.	Colo.			IW				36	Al					69	Bonham and Harvey 1983
28.	Utah[2]			NP					Al(grain)		.69			1,046	Acord 1970
									Al(grain)		.84			1,540	
29.	Nev.[2]	119		KG	.75			911	WC	31	.91			871	Jensen et al. 1964
30.	Wash.[2]	224		TF	.79			719	WC(112N)		.94			1,021	Heinemann and Van
									Al(112N)		.92			953	Keuren 1960
		224		OG	.79			595	WC(112N)		1.09			1,065	
									Al(112N)		.96			1,050	

Table 3 - Average daily response for beef and dairy cattle and response hectare^{-1} from N-topdressed grass and grass-legume mixtures[1]—Continued

		Nitrogen (kg ha^{-1})		Pure grass and animal response					Legume in mixture and animal response						
				Grass	Daily (kg)			Product	Legume		Daily (kg)			Product	
Item	State	Grass	Mixture	species	Steer	Cow	Calf	(kg ha^{-1})	Species	%	Steer	Cow	Calf	(kg ha^{-1})	References
31.	Wash.[2]	224		TF	0.88			885	WC(112N)	10	0.94			1,021	Van Keuren and
				TF					Al(112N)	43	.95			1,018	Heinemann 1958
		224		OG	.79			670	WC(112N)	14	1.09			1,065	
				OG					Al(112N)	52	1.01			1,102	
Dairy cattle response in 4% fat-corrected milk:															
32.	Va.			OG					Al			12.9		5,864	Blaser et al. 1969
				OG					WC			10.6		3,659	
				BG					WC,BT			11.6		4,711	
33.	Penn.			OG					Al					5,731	Sprague et al. 1952
				OG					WC					7,309	
				BG					Al					5,239	
				BG					WC					6,250	
34.	Ky.	112		OG		14.3		5,963	WC			17.3		6,180	Clark et al. 1966
		224		OG		13.5		6,726							
		336		OG		14.4		7,352							
35.	Wash.	202		OG		16.8			WC	29		18.4			Murdock and Hodgson 1954
36.	Va.			OG					WC			16.5			Thompson and Holdaway
				OG					Al			15.5			1954
				TF					WC			15.8			
37.	Minn.	135		OG,BG		16.8		6,551	Al,WC			17.1		5,859	Wedin et al. 1965
38.	Nev.[2]	448		OG		24.3		4,987	Al,WC			25.2		5,132	Jensen et al. 1971

[1]See table 1 for identification of grass and legume species.

[2]Irrigated pasture.

Animal Response ha^{-1}

Productivity of well-managed legume-grass mixtures in the United States (nonirrigated) frequently exceeded 400 kg of beef gain ha^{-1} (table 3). The average steer gain ha^{-1} from all experiments listed in table 3 was 385 kg. Mixtures of WC-grass generally yielded highest steer gain averaging 435 kg ha^{-1} followed by 400 kg ha^{-1} from BT-grass mixtures and 380 kg ha^{-1} from Al-grass mixtures.

In the West, where supplemental water was applied and some nitrogen added to the legume-grass mixture, steer gain ha^{-1} was appreciably higher, averaging 978 kg ha^{-1} compared with the 385 kg ha^{-1} from nonirrigated conditions. Again, WC-OG grass mixtures yielded highest gains averaging over 1,000 kg ha^{-1} but Al-grass mixtures were similar, averaging 970 kg ha^{-1}. The limited data on milk produced ha^{-1} are quite variable, but Al-OG was superior to WC-OG in Virginia; the reverse occurred in Pennsylvania (items 32 and 33, table 3).

Assuming efficient forage utilization among experiments (table 3), one can use animal response ha^{-1} to obtain an approximation of the quantity of N required to be applied to pure grass to match productivity of a legume-grass mixture. This comparison accounts for both yield and quality differences of the forage. An approximation, obtained by using the ratio of gain ha^{-1} from the legume-grass mixture and the N-topdressed grass relative to the N applied to the grass, showed nonirrigated WC-grass (table 3) to substitute for slightly over 200 kg of N ha^{-1}. The value for BT was about 170 kg of N ha^{-1} and for Al about 250 kg of N ha^{-1}. These substitution values provide important guidelines in making economic assessment of which pasture base to use.

The same question can be approached differently by using similar live weight gains from N-topdressed grass and legume-grass mixtures. Although such data are quite limited, results in table 3 reveal that approximately 200 kg of N ha^{-1} was required to produce approximately 400 kg of beef gain ha^{-1} from a productive legume-grass mixture. The 1:2 ratio of kg of N ha^{-1} to kg gain ha^{-1} is also useful for management decisions.

Substitution of Fertilizer-N for Legume-N to Produce Forage Dry Matter

A viable livestock industry requires efficient production of high forage dry matter yields. Nitrogen topdressings have served this need (table 4). However, legumes in combination with grasses can also give very acceptable dry matter production. The average legume-grass yields from all experiments shown in table 4 exceeded 7,800 kg ha^{-1}. In several experiments, yields exceeded 10,000 kg ha^{-1} and many produced 8,000 to 9,000 kg ha^{-1}.

The substitution of elemental N for legume N derived from the best legume-grass dry matter yield data (showing the legume's potential) reveals that about 200 to 215 kg of N ha^{-1} applied to pure grass was required for yields similar to WC-grass and RC-grass mixtures. Equivalent grass yields to a BT-grass mixture required about 235 kg of N ha^{-1} and for an Al-grass mixture about 275 kg of N ha^{-1}. In the Deep South, the Desmodium species (item 1, table 4) also demonstrated high N-fixation potentials of over 235 kg of N ha^{-1} when grown with BH and about 150 kg of N ha^{-1} with DG.

Factors in Choosing Pure Grass or Legume-Grass Mixtures

Of the major biological factors that must be considered in selecting pure grass or legume-grass mixtures (table 5), the general lack of persistence (factors 1, 2, and 5) and additional care needed in managing pastures to retain the legume component (factors 7 and 8) of mixtures are decidedly negative. Yet a producer would ideally develop a forage system to maximize profit from salable products (steer or calf live weight gain or FCM $animal^{-1}$ day^{-1}). This requires high-quality forage (ignoring supplements), which may be best obtained from a legume-grass mixture. On the other hand, breeding stock carried from year to year need only a maintenance ration during certain portions of the year. Temperate or subtropical grass pastures properly topdressed with N and heavily stocked can meet their needs. The concept of creep grazing or forward creep grazing is suggested as a management practice to fulfill both situations noted above. Virginia workers (Blaser 1982) have successfully used legume-grass mixtures in a flexibly managed three-paddock system of temperate forages for year-round feeding. One paddock (55 percent of the total 6.1 ha area) was WC-KG used for spring to late-fall grazing and two other paddocks of equal size were TF and RC. The latter two were used flexibly as (1) hay in late spring, (2) summer grazing, (3) accumulation of forage in late summer for winter grazing, and (4) for creep grazing at any time, allowing a high degree of selectivity to maximize daily energy intake. Hay and forage accumulations were altered, depending on the rainfall of the season. Calves were able to forward creep graze while cows were retained on base pasture heavily stocked. Stockpiled forage was used in fall and winter with hay harvested from the TF-RC paddocks and fed as needed during the winter. This system produced calves with daily gains of 1.02 kg. Increasing stocking rates from 1.23 cow-calf units ha^{-1} to 1.47 units ha^{-1} gave nearly identical weaning weights of 253 and 254 kg $calf^{-1}$ but increased live weight gain ha^{-1} by 19%. Cow live weights changed during the year, but seasonal effects were inconsequential.

Economic Considerations

Introduction of a legume into a grass sward increases animal performance, possibly shifts seasonal distribution of forage production, and possibly improves conception rates. Animal performance from legume-grass pasture results in heavier animals (26-33 kg) of possibly higher grade than obtained from grass. However, the U.S. marketing system, based on weight classes and subjective body condition scores, could negatively affect the value of the heavier animal if allocated to a higher weight class paying less kg^{-1} of body weight. Because of this dilemma, the weight and condition aspects will be assumed similar for

Table 4 - Dry matter yield (kg ha^{-1}) of nitrogen-topdressed grasses compared with total mixture yield from the same grass grown with legumes[1]

Item	State	Grass Species	Nitrogen applications to grass species (kg ha^{-1}) 34-56	67-95	112	126	140	196	224	280	300	336	448	560	1,120	Legume Species	Legume Yield	References
1.	Fla.	DG				9,400										DI	12,430	Kretschmer et al. 1973
																DH	9,850	
		BH				5,740										DI	12,650	
																DH	9,130	
2.	Fla.	BH			7,350				11,840				15,690			WC	11,380	Blue 1980
3.	Ala.	OG				5,880										RC	6,100	Hoveland et al. 1982
																BT	5,030	
		TF				7,260										RC	6,080	
																BT	5,190	
		TF						8,260								WC	7,360	
																RC	8,950	
																BT	6,640	
4.	Ky.	BD			6,470				9,560			11,940				RC	8,390	Templeton and Taylor 1975
																BV	7,380	
5.	Ky.	KG		4,480				6,610			7,950					WC	5,380	Taylor 1982
																RC	7,060	
																BT	7,620	
																Al	10,750	
		TF		6,160				8,400			10,420					WC	5,820	
																RC	7,500	
																BT	8,400	
																Al	10,190	
6.	Ky.	TF-KG[2]			5,300				7,500			9,200				WC	5,600	Taylor and Jones 1982
																RC	7,300	
																BT	8,000	
																Al	10,500	
7.	Ky.	OG-TF								8,840						WC	6,670	Doll et al. 1961
8.	Md.	OG		6,120				8,160		7,836						WC	8,837	Wagner 1954
9.	Pa.	OG			8,090											WC	6,930	Washko and Pennington 1956
																BT	6,610	
																Al	7,040	
		BG			6,100											WC	6,300	
																BT	5,650	
																Al	6,770	

Table 4 - Dry matter yield (kg ha^{-1}) of nitrogen-topdressed grasses compared with total mixture yield from the same grass grown with legumes[1]—Continued

Item	State	Grass Species	Nitrogen applications to grass species (kg ha^{-1}) 34-56	67-95	112	126	140	196	224	280	300	336	448	560	1,120	Legume Species	Legume Yield	References
		RG			8,270											WC	7,220	
																BT	6.030	
																Al	8,140	
10.	Iowa	OG	3,210	4,330			6,600			9,948						RC	8,490	Carter and
																Al	8,440	Scholl 1964
		BG	3,830	4,631			5,750			8,000						RC	8,504	
																Al	9,361	
11.	Mich.	OG	5,870		7,443				8,915							Al	8,028	Tesar 1974
		TF	6,374		7,947				9,190							Al	8,754	
		BG	6,616		7,846				9,198							Al	8,532	
		RG	5,910		7,524				9,258							Al	8,431	
12.	Wis.	OG					7,172			9,640				10,980	10,310	Al,WC	6,275	Schmidt and
		BG					5,450			7,400				7,844	7,844	Al,WC	6,950	Tenpas 1965
		TM					6,950			8,070				8,070	7,400	Al,WC	7,844	
13.	Wis.	OG	2,637		3,481				5,312							Al	6,119	Krueger and
		RG	3,302		4,609				6,955							Al	6,305	Scholl 1970
14.	Calif.	NP	9,190	10,870				12,102								SC	9,410	Jones 1967

[1]See table 1 for identification of grass and legume species.

[2]Sod-seeded.

Table 5 - Comparative factors in choosing the use of a legume-grass mixture or pure grass for pastures

Factor	Degree of factor: N-fertilized pure grass	Degree of factor: Legume-grass mixture
1. Soil property sensitivity	Less	More
2. Establishment problems	Less	More
3. Nitrogen applications	More	Less
4. Pollution (N losses)	More	Less
5. Perenniality	More	Less
6. Midsummer growth (tropical grasses)	More	Less
7. Dry matter yield after 3 to 4 years	More	Less
8. Management of pastures (plants)	Less	More
9. Management of animals (gains)	More	Less
10. Animal performance	Less	More
11. Animal days unit^{-1} area	More	Less
12. Animal product unit^{-1} area	More	Less

legume-grass and N-fertilized grass pastures. With this assumption and if land area is fixed, the choice of pasture depends then on the production (including cost) of salable animal product ha^{-1}. Wide variations in salable product from both legume-grass and N-grass systems makes comparative economics difficult. Grazing studies usually give the advantage to legume-grass systems in animal daily gain and in gain ha^{-1} until N application rates on N-grass systems exceed 200 kg ha^{-1}. Given this biological advantage (at least in the range of N-applications practiced by the typical farmer), why are so few hectares in the United States invested with legumes, especially when so many hectares receive only 25 to 30 kg N? Unofficial estimates (H.C. Gilliam, Jr., regional analyst, Southern Region Economic Research Service, USDA, personal communication) place the proportion of all Southeastern U.S. "improved" pastures that contain legumes at somewhere between 20 and 25 percent.

Establishing and maintaining legumes in grass swards requires a major change in the way an operation is managed, many elements of which are difficult to quantify. Like any technique, it requires a stock of experience and experimentation for its success. It is doubtful that a livestock operator would seed all of his land area to legumes, since certain classes of animals do not require the quality common to such swards. In addition, renovation (introducing a legume into a grass sward) of grass pastures causes the producer to lose time in the production of salable product, or at least causes him to temporarily divert resources otherwise employed in the absence of renovation. The choice between legume-grass and N-grass systems depends on the costs and returns associated with each. In the past, as land prices increased relative to fertilizer prices, substitution of fertilizer for land was undertaken. As N fertilizer prices increased relative to renovation and legume maintenance costs, legumes were substituted for nitrogen. It is probable, however, that much of this latter substitution was a one-time substitution. While much research shows the beneficial effects of legumes on animal performance, very few experiments have included analyses devoted to an accounting of the costs associated with management of animals on legume-grass swards. Initial unsuccessful attempts by farmers to establish long-lasting stands of clover, perhaps due to an unawareness of complications in the animal-forage interaction, (associated with the disease-insect complex and with timing of harvests) probably led to unanticipated management costs and, thus, a reevaluation of the tradeoff between legume N and fertilizer N.

Very few economic studies have addressed the question of tradeoffs involved in the substitution of legume-N for fertilizer N. Table 6 gives those items of cost most often cited and the ones used in our following comparison. An established sod of tall fescue with an expected stand life of 10 years or more will be compared when either renovated by

Table 6 - Variable cost categories ($\$$ ha^{-1}) for white clover-fescue vs. N-fescue systems

	Establishment or liming year		Maintenance years	
Item	Clover-fescue	N-fescue	Clover-fescue	N-fescue
Clover seed	31			
Fescue seed	6			
Inoculant	1			
Lime	129	128		
P and K	96	65	81	65
Nitrogen (200 kg)		88		88
Fuel, oil, repair	20	15	10	15
Labor	19	14	10	14
Herbage foregone	126			
Total	428	310	101	182

introducing ladino clover or topdressed with N. Labor, fuel, oil, and machinery repair are saved by not having to spread N fertilizer and are compared with usage levels for these variables in the renovation and maintenance phases of legume-grass systems. Potassium, phosphorus, and lime requirement differences also occur. A comparison of the items listed in table 6 was performed utilizing current North Carolina State University (Standaert 1983) budgets for fescue fertilized at 200 kg ha^{-1} (applied in three applications) and fescue-ladino clover seeded at 3.5 kg ha^{-1} (clover seed). Renovation of the fescue sod was accomplished in September by a light disturbance of the soil into which the clover seed was drilled. Deferred grazing of animals on fescue pasture during the renovation phase was charged the 1,800 kg ha^{-1} of dry matter (3,000 kg ha^{-1} if not renovated vs. 1,200 kg ha^{-1} if renovated) it would have produced in the absence of renovation (7 cents kg^{-1}). It was assumed that all future costs would increase at the same rate as inflation; that is, real costs are constant over the period. However, future costs for each system are discounted at a real before-tax interest rate of 6 percent per year to reflect returns foregone to the investment. At current input prices (in U.S. dollars) variable costs for such renovation were $\$428$ ha^{-1}. Annual variable maintenance costs were $\$101$ ha^{-1} for the legume-grass system. The N-fescue system was divided into two phases also, a liming phase and a maintenance phase. It was assumed that although soil pH requirements for the N-fescue system are lower than for the legume-fescue system, high rates of N in the N-fescue system would cause the soil to acidify faster than in the legume-grass system. The liming phase for the N-fescue system occurred in the first year with no lime applied thereafter for 5 years. In this example, lime applications were equalized in both systems. Liming-year variable costs are $\$310$ ha^{-1}, and maintenance-year variable costs are $\$182$ ha^{-1}.

A major risk associated with the renovation of a grass sod is variation in clover-stand life. Ladino clover can survive up to 5 years under good management, but survival is frequently much less. Springtime competition for water, light, and nutrients between the grass and legume will be severe unless some method of controlling grass growth is undertaken. Legumes existing in a cool season sward during the summer are easily overgrazed to the detriment of clover stands.

On the other hand, the disadvantages associated with short clover-stand life are relatively less severe as N prices increase. An illustration of the interaction of clover-stand life and N prices on the cost advantage of legume-grass over N-grass (200 kg ha^{-1}) are given in table 7. All cost items are evaluated at current U.S. prices except nitrogen, which is allowed to vary in the N-fescue system. Discounted variable costs in a given year are added to those which were invested in previous years. Cumulative cost advantages were derived by subtracting legume-fescue costs from N-fescue costs for each year of stand life and for each N price.

If the probability of all stand lives were equal, the expected legume-grass cost advantage, as

Table 7 - Cost advantage ($ ha^{-1}) of ladino clover-fescue over N-fescue, by stand life and nitrogen price[1]

N price ($ kg^{-1})	Clover stand life (years) 1	2	3	4	5	Mean
0.36	-133	-72	-15	39	90	-18
0.44	-117	-41	30	98	162	26
0.52	-101	-10	76	157	233	71
0.60	-85	21	121	216	305	116
0.68	-69	52	166	274	376	160

[1]Computed as variable cost of N-fescue minus variable cost of ladino clover.

represented by the mean column in table 7, would be positive at current nitrogen prices (around 44 cents kg^{-1}). Nitrogen prices for this situation would have to decrease to 40 cents kg^{-1} for the cost advantage of ladino-fescue to become zero.

Table 7 shows that for those items to which specific costs may be attached, there is an advantage to the use of legumes in pasture for the production of beef and milk if all stand lives are equally probable. For two reasons, table 7 should be viewed with caution. First, not all costs are included. The additional fencing or management time a legume-grass system might require are difficult to assess in our example. Second, the odds associated with stand life are not all equal. For the inexperienced manager, high probability weights may be attached to stand lives of 1 to 3 years but much lower ones to stand lives of 4 to 5 years. This could make the expected cost advantage negative even at current or higher N prices. As the manager becomes more experienced with legumes, the probabilities shift in such a way that longer stand lives receive higher probabilities, resulting in increasingly more favorable cost advantages to legume introduction.

The example above tells a partial story. For cost calculations of this type to have meaning for forage choices, they must be compared to benefits flowing from each alternative, or at least benefits to each system must be equalized in some way. To some extent, this has been done by assuming that a hectare of fescue fertilized at 200 kg ha^{-1} will produce as much beef or milk as a hectare of clover-fescue. Benefits ignored in such an equalization are differences in the quality, quantity, and subsequent value of hay produced by each system.

The management elements of introducing a legume into a grass system are not well studied and imply a whole host of activities and opportunities essential to stand persistence. Examples are greater movement of cattle, altered fencing arrangements, summertime grazing, creep grazing, altered hay-making schedules and quantities, increased observation time on animals for signs of bloat and on the forage itself for signs of insect or disease attacks, and decreased stands. Some of these elements apply equally to intensively utilized N-grass systems, where stand survival is not an issue, but efficient utilization of forage is. None of these actions are costless, and any comparative research should take them into account.

Important specific items for which values are not available for comparing legume-grass and N-grass systems are as follows:

1. Cost-Related Items

   a. Time-and-motion estimates associated with those management factors expected to increase the odds of increasing legume stands when seeded into grass pastures and the demands of maintaining acceptable quality in pure grass pastures.

   b. Estimates for additions to labor, management time, and fencing to decrease chances of adverse animal response (for example, bloat for legumes and tetany for grasses).

   c. Estimates of the effect of altered seasonal production due to legume introduction on the amount, and thus the cost and quality, of hay produced.

   d. Estimates of costs associated with alternative renovation techniques, such as surface seeding of clover in late winter, as well as effects of each technique on stand survival.

   e. Estimates of differential hay drying times for pure grass versus legume-grass systems.

2. Benefit-Related Items

   a. Net (after culling) effects of each forage system on conception rate.

b. Estimates of differences in animal gain, hence body weight and condition, and subsequent value, as conferred by the market system for each forage system, based on breed type and by animal frame size within breed type.

c. Estimates of differences in compensatory gain by animals on each forage type.

Research Needs

As evident in table 3, a considerable number of grazing studies have been conducted in the United States, comparing, in some way, grass and legume-grass treatments. Most of these studies are fragmented (providing information for apparent local needs) and generally lack the full range of treatments that are needed to provide direct comparisons. Further, few studies are in print in the United States that both provided adequate pasture measurements or were conducted year-round (grazing and stored feeding) and focused on biological and economic comparisons of legume-grass and N-grass as forage sources. Areas that need further consideration are noted below:

1. Survey of the literature and compilation of data that is in local use, but not in print, to provide comprehensive evaluation of legume-grass vs. N-grass systems for year-round feeding.

2. Evaluation of present modeling efforts through validation and prediction using results from item 1 above to determine likely role of modeling to fill in gaps present in current experimental data.

3. After careful examination of items 1 and 2, regional planning needs initiated using small teams of active scientists representing necessary disciplines to design and conduct critical experiments at selected locations on year-round forage-animal systems.

   General areas to be considered within each experiment are:

   a. Forage species selection, establishment, subsequent maintenance, and harvesting practices.

   b. Soil physical and chemical properties.

   c. Forage utilization and subsequent animal daily and ha^{-1} responses.

   d. Animal breed selection, health, and reproduction.

   e. Animal feeding systems during winter.

   f. Economic considerations at all levels.

4. Development of management systems that will provide year-round forage to meet varying requirements of different classes of livestock.

5. Consideration of year-round systems with regard to:

   a. Improvement of available legumes and grasses and the introduction of new species for enhanced or sustained summer production and seasonal yields.

   b. Establishment and management of pure and mixed stands for efficient production and stand maintenance.

   c. Seasonal forage quality and yield patterns.

6. Application of the concept of grazing pressure to animal nutrient requirements and use of the concept in management.

7. Use of supplemental energy and protein feeds.

8. Development of animal breeds with improved liveweight gains and carcass characteristics when grazing forages.

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Discussion

Marten: It was alluded to in your paper that the summer favored grass growth. For us it is the legume which is dominant in summer.

Burns: This is not true for us--south is in contrast to the north.

Lancashire: What is the average persistence time of legumes? What are the methods of renovation?

Burns: Perenniality varies appreciably, can last up to 12 years in Northeastern United States. However, I've noted with treatments involving both grass and legume, the legumes often don't last.

Sod seeding is looking good when paraquat and insecticides are used. Delayed sod seeding until October is successful with the use of paraquat alone.

Runge: What is the difference between the northern and southern latitudes on persistence of legumes?

Burns: Northern latitude persistence is probably better but depends on winter cover.

Knight: We recommend for Southeastern United States reinoculating and reseeding at half the seeding rate in the second year to help ensure persistence of a stand.

Rumbaugh: Persistence under dryland/low competition can be up to 30-40 years.

Field: A positive effect on conception rate is shown in your paper. Was this included in the economic analysis?

Burns: No, it was primarily the cost data.

Helyar: It is unusual for sown white clover and other legumes to survive for more than 2 years. There is a need to define perenniality. Is it survival of the species or survival of the same plant?

Burns: The definition of perenniality is that the plant itself persists independent of reseeding. But agreed, persistence needs to be better defined.

Harris: Is grazing management a major factor in poor persistence of legumes?

Burns: Poor management will predispose legumes to disease and pest damage.

Field: Keith Steele has done a lot of work on factors affecting persistence of white clover, using fumigation to eradicate pests and diseases. Are you looking at this area?

Knight: Work on fumigation of soil to improve establishment is very limited. We get good responses to control of nematodes.

Steele: In New Zealand, we can get very good responses in N fixed and DM production through control of nematodes, up to 100% increase.

Heichel: Evidence from Canada and Minnesota is that nematodes are deleterious to alfalfa productivity. Resistance to pests is now an objective of breeding programs.

Marten: It has been observed that pest problems have become more and more serious with increasing lucerne acreages in New Zealand. Is this a general trend with legumes?

Rumbaugh: We have observed this with safflower in Central United States.

Energy Budgets for Legume-Based vs. Fertilizer Nitrogen-Based Forage Systems

G.H. Heichel[1]

Abstract

Calculation of energy budgets for forage production systems incorporating legumes, grasses, or rotations of legumes and grasses revealed substantial differences among cropping systems in requirements for fossil fuels. Fossil fuel requirements are greater for forages established annually than for perennial forages, are greater for grasses fertilized with nitrogen than for legumes, and are greater for crop rotations based primarily upon nitrogenous fertilizers than those which incorporate perennial or annual legumes. The fossil fuel requirements for a particular forage species also vary with method of establishment, dependence upon irrigation, yielding ability, and method of harvesting or preservation. In comparison with grasses, forage legumes require less fossil fuels because of their capability to symbiotically fix atmospheric nitrogen in lieu of reliance upon fertilizer sources of nitrogen. Although production of forage species requires less fossil fuels than the production of most other crops, except trees grown for lumber, the differences in energy requirements of forages resulting from choice of crop and method of management provide opportunities to develop regimens for raising animals with less dependence upon fossil fuels.

Introduction

Decisions on the inputs and the management practices for use with either grazed or harvested forages are traditionally based on economic criteria. The benefits of forage crops to soil conservation and stabilization, or to conservation of fossil fuel resources, are less easily quantified in economic terms than are the nutritive benefits to animal production. The recent development of energy auditing methods (Heichel 1976, Aiken et al. 1983) for cropping systems has facilitated the identification of characteristics of forage-based cropping systems related to efficient usage of fossil energy resources (Heichel 1977, 1978, 1982; Heichel and Martin 1980). A summary of the salient features of these investigations follows.

Energy Audits of Cropping Systems

The energy audit, a system of accounting for energy use, provides the framework for assessing the allocation of fossil energy resources in crop production. The energy audit identifies the indirect (off-the-farm) energy usage required to manufacture inputs purchased by the farmer. Examples of these are fertilizers, agricultural chemicals, tractors, implements, and buildings. The audit also identifies the direct (on-the-farm) usage of fossil energy, principally as fuel consumed by tractors and machines in applying manufactured inputs during tillage, planting, pest control, harvesting, and storage operations (Kjelgaard 1979, Pimentel 1980). The energy budget of the cropping system is the summary of the "operating costs" and production outputs of the system in energy units.

Energy budgets for several cropping systems will be discussed. Limitations of space will not allow a complete review of energy budgets that are tabulated elsewhere (Heichel 1977, Heichel and Martin 1980). As an alternate approach, comparisons of energy efficiency of cropping systems will be made. The efficiency of fossil energy use will be calculated from the budgets as the ratio of digestible energy in the harvested crop to the total fossil energy inputs in production (Heichel 1977, 1978) or as the ratio of the mass of commodity produced to the total energy inputs in production (Fluck 1979).

Energy Budgets of Single-Year Forage Production Systems

The energy costs of producing a forage depend upon species of crop, method of establishment, cultural inputs, source of water, and method of harvesting or conservation. Several of these variables will be reviewed.

Legume vs. Grass-Based Systems

Corn (*Zea mays* L.) for silage is the principal grass and alfalfa (*Medicago sativa* L.) is the principal legume grown for harvested forage in the United States. The energy inputs to produce these forage species differ substantially (tables 1, 2). About 41% of the energy budget for corn silage production was expended for nitrogen fertilizer. Another 29% was consumed as fuel, 19% as machinery, but only 3.3% was utilized as pesticides. Phosphorus and potassium fertilizers and seed comprised the remaining 8% of the energy budget. The 40,910 kg/ha of silage returned 9.06 kcal of digestible energy/kcal of fossil fuel energy used in production.

The production of alfalfa hay required only 73% of the fossil energy resources as the production of corn silage (table 2). The principal savings were in nitrogen fertilizer and in the liquid fuel requirements of machinery operation. Because the legume fixes nitrogen, it is free of dependence upon the nitrogenous fertilizer which is the largest energy input to corn production. Also, there are far fewer field and storage operations for alfalfa than for the corn silage, which results in a smaller allocation of machinery for alfalfa production compared with corn and in a reduced energy usage by the machinery.

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Table 1 - Energy budget of corn silage production in southeastern Minnesota (adapted from Heichel 1977)

Item	Quantity/ha	kcal/ha
Input		
Labor	6.83 h	
Machinery	44 kg[1]	799,200
Fuel	142 L	1,200,000
Nitrogen	114 kg	1,732,800
Phosphorus (P_2O_5)	45 kg	135,000
Potassium (K_2O)	39 kg	62,400
Seed	17 kg	119,680
Pesticides	5.7 kg	137,940
Drying		
Electricity	2	
Transportation	2	
Total fossil energy input		4,187,020
Output		
Dry matter yield (70% H_2O)	40,910 kg	37,922,000
Digestible energy output/ fossil energy input		9.06

[1]Values for machinery in this and subsequent tables were computed according to procedures of Doering (1980). Energy embodied in machinery will vary with the farm enterprise and with implement composition (that is steel, copper, aluminum, and rubber).

[2]Values aggregated with machinery.

It is important to note that the energy budget of the forage legume varies with the climate in which the crop is grown (table 3). The fossil energy needs of producing baled hay in Colorado are only 71% of those of hay production in Minnesota. This is attributable to differing energy needs for fertilizers and transportation (Cook et al. 1976). However, the crop is only 17% as productive in Colorado as in Minnesota. Thus, while the energy needs of production are far less in Colorado than in Minnesota, the digestible energy yield per unit of fossil energy input is 320% greater in Minnesota than in Colorado. These results suggest that, for forage crops that have relatively comparable energy inputs, the greater efficiency of energy usage will occur when the crop is grown in more favorable environments.

Method of Establishment

The energy needs of establishing forages have seldom been investigated. Because establishment of alfalfa in Minnesota and other states with a herbicide or with a companion crop may result in an economic loss the seeding year, it is important to determine whether alfalfa establishment incurs an energy cost that is not revealed in the economic analysis.

Establishment of alfalfa with a companion crop of oats (*Avena sativa* L.) is the prevalent practice in Minnesota, and the energy budget of this system is shown in table 4. The greatest energy cost (36%) was incurred for seed. Fuel consumption accounted for 34% of the crop energy budget and was the second most significant component. Machinery and potassium fertilizer were other significant inputs. About 3% of the energy budget was needed for fertilizer nitrogen, an input needed for optimal growth of the companion crop.

Alfalfa establishment with a herbicide is similar to establishment with a companion crop in that the greatest energy use is associated with seed, liquid fuel, and transportation, which account for 82% of the crop energy needs (table 5). Establishment with a herbicide incurs 3% less energy use than establishment with a companion crop, chiefly because of energy savings in seed and transportation. Alfalfa establishment with a herbicide often permits two hay harvests in the seeding year; therefore, total dry matter production is greater than for the companion crop system, where only grain is harvested. Thus, the energy balance of alfalfa establishment with a herbicide is 100% greater at 4.5 units of digestible energy per unit of fossil fuel energy compared with companion crop establishment.

Table 2 - Energy budget for the second or third production year of baled alfalfa hay in southeastern Minnesota (adapted from Heichel and Martin 1980)

Item	Quantity/ha	kcal/ha
Input		
Labor	7.2 h	
Machinery	852 kg	19,905
Liquid fuel	92 L	1,050,090
Electricity		
Nitrogen		
Phosphorus (P_2O_5)	34 kg	102,000
Potassium (K_2O)	68 kg	108,800
Limestone	2,652 kg	835,390
Seed		
Irrigation water		
Insecticides		
Herbicides		
Drying		
Transportation	3,655 kg	939,335
Total fossil energy input		3,005,520
Output		
Dry matter yield (15% H_2O)	10,000 kg	23,104,000
Digestible energy output/ fossil energy input		7.56

Table 3 - Energy budget for the second or third production year of baled alfalfa hay in eastern Colorado (adapted from Cook et al. 1976)

Item	Quantity/ha	kcal/ha
Input		
Labor	18.8 h	
Machinery	681 kg	14,300
Liquid fuel	142 L	1,620,790
Electricity		
Nitrogen		
Phosphorus (P_2O_5)	91 kg	273,000
Potassium (K_2O)		
Limestone		
Seed		
Irrigation water		
Insecticides	1.2 kg	29,000
Herbicides		
Drying		
Transportation	845 kg	217,165
Total fossil energy input		2,154,255
Output		
Dry matter yield (15% H_2O)	1,718 kg	3,881,000
Digestible energy output/ fossil energy input		1.80

Irrigated Compared With Rainfed Systems

Alfalfa hay production under irrigation is practiced by some growers. Since the use of irrigation varies according to precipitation within areas of production, this comparison is based upon production systems for the same geographical region of Minnesota (tables 2, 6).

Excluding the energy required to build the irrigation system, the energy needs of irrigated alfalfa were about 20% greater than those of nonirrigated alfalfa. Other slight differences in crop nutrition and management were insufficient to cause modifications in energy needs between the two cropping systems. Compared with nonirrigated alfalfa, the irrigated alfalfa yielded 18% more dry matter with a 20% increase in energy use. Thus, the energy efficiency of irrigated alfalfa, 7.43, is slightly less than that of the nonirrigated alfalfa.

Effect of Harvesting or Processing Method on Energy Use

Like the comparison of species or establishment methods, comparisons of energy use by different harvesting methods are best made in a common geographic area. Fuel consumption comprised 75% of the energy budget for production of baled alfalfa hay in Colorado (table 3). Phosphorus fertilizer utilized 13% of the energy and machinery another 0.7%, with the remainder accruing to pesticides and transportation. In comparison, the production of alfalfa pellets from dehydrated herbage was substantially more energy intensive (table 7).

Like the production of baled hay, the greatest energy input to dehydrated alfalfa was from fuel, which comprised 55% of the energy budget (Cook et al. 1976). About 13% of the energy budget was devoted to fuel use in drying the herbage and forming a dehydrated pellet. The transportation energy required in producing dehydrated alfalfa was more than double that of producing baled alfalfa. However, the dehydration and pelleting yielded a product that was less expensive than baled hay to transport over long distances.

The greater energy needed for fuel, machinery, fertilizer, drying, and transportation resulted in dehydrated alfalfa being only 60% as efficient in use of fossil energy as baled alfalfa hay. Although the yields of digestible energy for both cropping systems were similar, alfalfa processed as hay returned 1.80 kcal digestible energy/kcal of fossil fuel energy, while dehydrated alfalfa returned only 0.93. Thus, the energetics of forage production are strongly modified by the intended use of the forage product.

Table 4 - Energy budget of alfalfa establishment with an oat companion crop in southeastern Minnesota (adapted from Heichel and Martin 1980)

Item	Quantity/ha	kcal/ha
Input		
Labor	5.3 h	
Machinery	1,745 kg	33,400
Liquid fuel	90 L	1,027,260
Electricity		
Nitrogen	17 kg	97,300
Phosphorus (P_2O_5)		
Potassium (K_2O)	136 kg	217,600
Limestone[1]		
Seed	13 kg alfalfa, 67 kg oats	1,074,000
Irrigation water		
Insecticides	1.2 kg	29,000
Herbicides		
Drying		
Transportation	2,027 kg	520,940
Total fossil energy input		2,999,500
Output		
Dry matter yield (10% H_2O)	2,548 kg oat grain	6,750,920
Digestible energy output/ fossil energy input		2.25

[1] Prorated over production years.

Table 5 - Energy budget of alfalfa establishment with an herbicide in southeastern Minnesota (adapted from Heichel and Martin 1980)

Item	Quantity/ha	kcal/ha
Input		
Labor	6.4 h	
Machinery	1,465 kg	30,375
Liquid fuel	95 L	1,084,330
Electricity		
Nitrogen		
Phosphorus (P_2O_5)	45 kg	135,000
Potassium (K_2O)	136 kg	217,600
Limestone[1]		
Seed	14 kg	868,000
Irrigation water		
Insecticides		
Herbicides	5.7 kg	138,000
Drying		
Transportation	1,717 kg	441,270
Total fossil energy input		2,914,575
Output		
Dry matter yield (15% H_2O)	5,682 kg	13,127,690
Digestible energy output/ fossil energy input		4.50

[1]Prorated over production years.

Energy Budgets of Rotations or Multiyear Cropping Systems

Most cropping systems consist of sequences of different species of crops, often nonlegumes and legumes, instead of the single-year examples discussed above. For crop sequences, the same principles apply in calculating energy budgets as are used for single-year crops. The main difference is that the duration of the crop sequence, not the single crop year, is the basis for calculating energy inputs and the efficiency of utilization. For the sake of brevity, detailed energy budgets of crop rotations will not be presented, but briefer summaries of energy efficiency instead.

Continuous Grass Compared With Rotations Containing Legumes

Continuous corn is a common but relatively energy-intensive production system in the midwestern U.S. Continuous corn grown either for grain or for forage is sustained with nitrogen fertilizer produced at the expense of nonrenewable energy resources. The fossil energy inputs to continuous corn grown for forage average about 1.24 gal oil/ha/day (table 8, rotation 1). Nitrogen fertilizer accounts for about half of this energy requirement.

A continuous monoculture of corn or another fertilizer-N based grass may be rotated with forage or grain legumes to provide a more energy-efficient cropping system. Under proper management, substantial nitrogen remains in the soil for a succeeding crop when alfalfa is used in the rotation. The protein in roots and unharvested regrowth of a 2- or 3-year-old alfalfa stand is equivalent to 215 kg N/ha. About 80% of the total, 168 kg N/ha, is fixed by symbiosis at no expense to fossil energy resources. The remaining 45 kg N/ha is derived from mineralization of soil organic matter.

Because the nitrogen fixed by symbiosis that is in the residual plant material incorporated into the soil represents a net accretion beyond that harvested by the grower, it represents an energy credit that can be allocated to a subsequent crop. In the case of a two corn/oats/two alfalfa rotation (table 8, rotation 2), the nitrogen becomes available during the first and second years of corn and may reduce the nitrogen fertilizer requirement of the crop by 50%. Compared with continuous corn, the reduction in energy for fertilizer, direct fuel consumption, and other inputs in this rotation is nearly 38%. The ratio of digestible energy yield to fossil energy input shows that the energy balance of the rotation has been improved 28% by including alfalfa and the companion crop.

Table 6 - Energy budget for the second or third year of production (under irrigation) of baled alfalfa hay in southeastern Minnesota (adapted from Heichel and Martin 1980)

Item	Quantity/ha	kcal/ha
Input		
Labor	11.8 h	
Machinery[1]	772 kg	20,285
Liquid fuel	76 L	867,460
Electricity		
Nitrogen		
Phosphorus (P_2O_5)	34 kg	102,000
Potassium (K_2O)	135 kg	216,000
Limestone	2,652 kg	835,390
Seed		
Irrigation water[2]	10 cm	696,250
Insecticides		
Herbicides		
Drying		
Transportation	3,633 kg	933,680
Total fossil energy input		3,671,065
Output		
Dry matter yield (15% H_2O)	11,800 kg	27,262,714
Digestible energy output/ fossil energy input		7.43

[1] Exclusive of irrigation system.
[2] Energy for pumping H_2O.

Table 7 - Energy budget for the second or third production year of production of dehydrated alfalfa pellets in Colorado (adapted from Cook et al. 1976)

Item	Quantity/ha	kcal/ha
Input		
Labor	20 h	
Machinery	1,560 kg	32,760
Liquid fuel	208 L	2,374,110
Electricity		
Nitrogen		
Phosphorus (P_2O_5)	277 kg	831,000
Potassium (K_2O)		
Limestone		
Seed		
Irrigation water		
Insecticides	1.2 kg	29,000
Herbicides		
Drying		560,000
Transportation	1,893 kg	486,500
Total fossil energy input		4,313,370
Output		
Dry matter yield (8% H_2O)	1,594 kg	4,005,000
Digestible energy output/ fossil energy input		0.93

Table 8 - Inputs of fossil energy, average crop yield over the rotation, and energy efficiency of crop rotations incorporating forage and grain legumes (adapted from Heichel 1978)

Item	Rotation 1 (continuous corn)	Rotation 2 (2 corn/oats/ 2 alfalfa)	Rotation 3 (3 corn/3 soybean/ wheat/3 alfalfa)
Fossil energy input (gallons crude oil equiv./ha·day)	1.24	0.77	0.69
Crop yield (kg dry matter/ha)	8,643	8,165	6,843
Energy efficiency (digestible energy yield/fossil fuel input)	6.1	7.8	8.3

Greater reductions in energy use can be achieved by lengthening the rotation to incorporate both annual and perennial legumes. The fossil fuel input of a three corn/three soybean (Glycine max L.)/wheat (Triticum aestivum L.)/three alfalfa rotation (table 8, rotation 3) is 44% less than that of continuous corn. The largest decrease in fossil energy use is attributable to a reduced need for nitrogenous fertilizer, but fuel and other inputs are also conserved. Compared with continuous corn, the energy balance of this rotation including perennial and annual legumes has been improved 36%.

Fertilizer N-Based Forage Grass Systems

In grass pastures, the productivity and energetic efficiency are strongly influenced by the level of applied nitrogen fertilizer (fig. 1), which accounts for most of the energy used in production (Leach 1975). Productivity of ryegrass (Lolium perenne L.) in the United Kingdom increased from 9,400 kg of 15% moisture dry matter/ha at 100 kg N/ha to 15,600 kg dry matter/ha at 450 kg N/ha. Because yield did not increase in direct proportion to rate of fertilization, the energetic efficiency was nearly twice as great at 100 kg N/ha as at 450 kg N/ha.

The energetic efficiency of ryegrass harvested either as hay or as silage also decreased with increasing nitrogen level (fig. 2). At both N levels, silage was energetically more efficient than hay when both products were grown at yield levels of either 10,600 kg of 15% moisture dry matter/ha at 250 kg N/ha or 12,000 kg of 15% moisture dry matter/ ha at 350 kg N/ha. The difference in energy efficiency was attributable to storage of grass silage as a high-moisture forage with a lower fossil energy input than hay, which required drying in this example (Leach 1975).

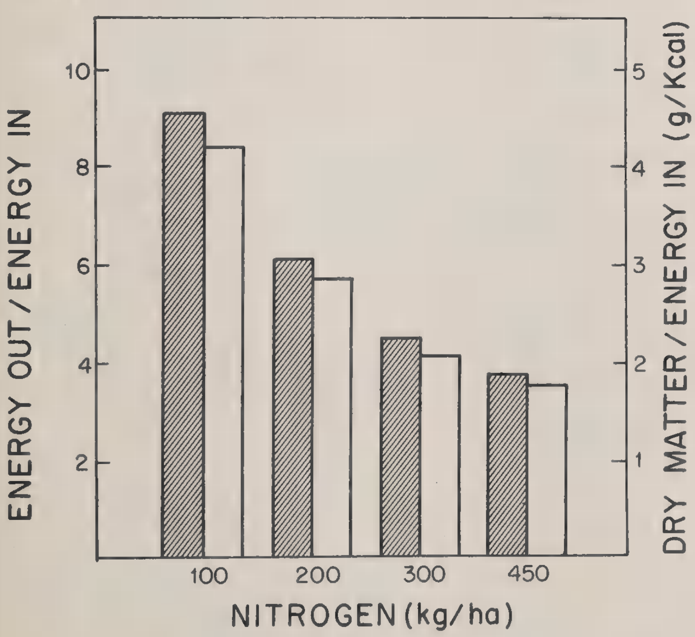

Figure 1--Digestible energy (shaded bars) and dry matter (open bars) output per unit of fossil energy input for grass pasture fertilized at four rates of nitrogen (adapted from Leach 1975).

Energy Usage of Forage--Animal Systems

The foregoing examples of greatly different energy efficiencies of cropping systems prompt the question as to whether these results might lead to differences in fossil energy usage among different systems of animal production. There have been few attempts to answer this question.

Feedlot

The fossil energy usage of an animal production system is a function of animal age and size, feed conversion efficiency, diet, degree of mechanization, and size of enterprise (Hughes 1976). Small confinement-feeding enterprises may use less energy than larger ones, although economies of scale may be more evident with younger than older animals (fig. 3). A corn silage diet for calves and yearlings resulted in less fuel use per kilogram of live-weight gain than did a diet of grain plus silage. The energetic advantage of the silage-based system increased with size of enterprise for both calves and yearlings.

Range-Feedlot

Analysis of four feeding regimens for cattle from birth to market in Colorado showed that the fossil energy needs of production varied with age of animal and the system of forage production chosen (Ward et al. 1977a, 1977b). For example, confinement feeding of forages to the cow and calf from birth to a calf weight of 180 kg required nearly three times the fossil fuel energy necessary for the cow to rear the calf on range with a small supplement of concentrate (table 9). Backgrounding a beef animal on irrigated pasture was about double the

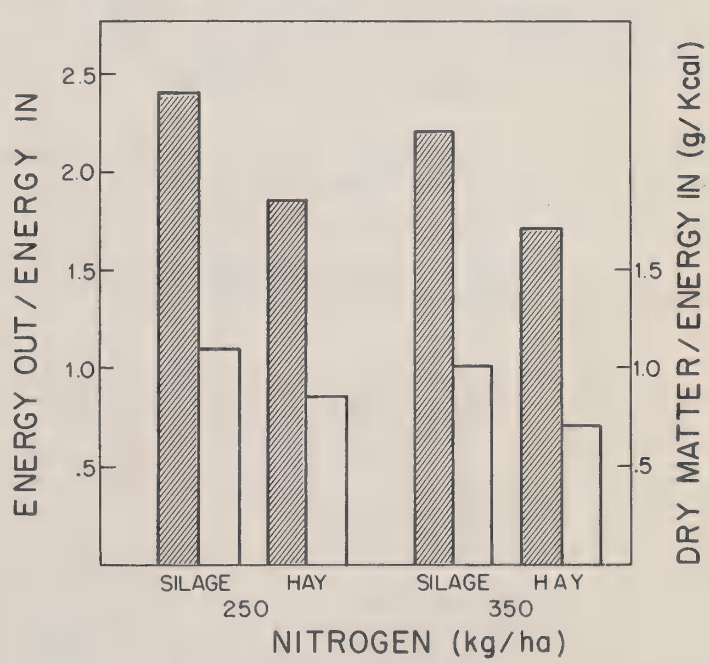

Figure 2--Digestible energy (shaded bars) and dry matter (open bars) output per unit of fossil energy input for grass silage and hay fertilized at two rates of nitrogen (adapted from Leach 1975).

energy-intensiveness as using range, corn silage, or a combination of corn silage and hay. Finishing feeder cattle on hay and silage was only slightly more energy efficient than was feeding ground or flaked corn. The various management options can be chosen to result in nearly a 50% range in fossil energy needed to raise an animal from birth to slaughter (table 9).

Dairy

A similar study in the United Kingdom (Leach 1975) showed that the energy cost of raising a dairy heifer with grass pasture and hay fertilized with high levels of nitrogen was nearly 44% greater than the energy cost of raising the animal on forage fertilized with lower levels of nitrogen (table 10).

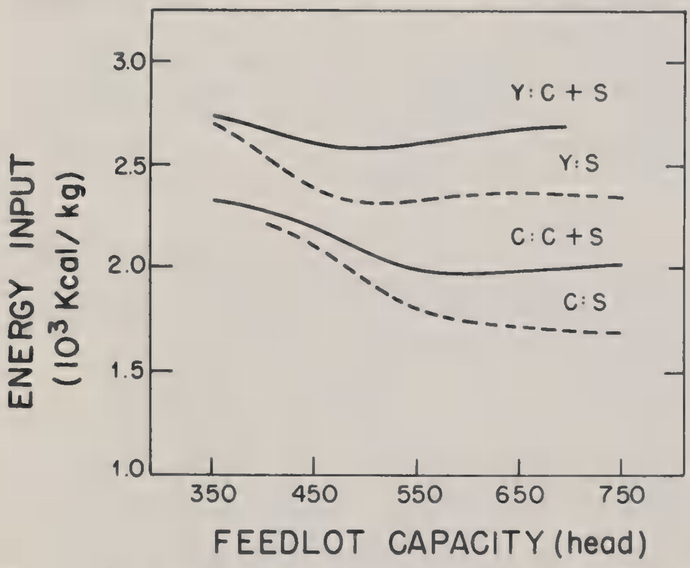

Figure 3--Fossil energy inputs per kilogram of live weight gain for yearlings (Y) and calves (C) fed either silage supplemented with corn grain (C+S) or silage (S) in feed lots of various capacities (adapted from Hughes 1976).

Table 9 - Fossil energy use of four feeding regimens for rearing beef calves (adapted from Ward et al. 1977)

Regimen	Fossil energy input, 10^3 kcal/animal: Birth to 180 kg	180 to 315 kg	315 to 495 kg	Total
a	(Confinement forage feeding) 2,788	(Irrigated pasture) 1,830	(Flaked corn) 3,023	7,641
b	(Mountain winter feeding) 2,560	(Corn silage) 858	(Ground corn) 2,927	6,345
c	(Summer range, winter feeding) 1,600	(Corn silage, alfalfa hay) 810	(Corn silage) 2,600	5,010
d	(Plains supplement, 0.45 kg/day) 992	(Plains) 774	(Alfalfa hay) 2,398	4,164

Future Research

These illustrations show that it should be possible to produce animals with less fossil fuel through the use of certain feeding regimens. Unfortunately, the differential pricing of various forms of energy in the United States often makes energy-efficient animal production methods uneconomical (Hughes 1976). This is because rates of gain are slower on energy-efficient, forage-based systems than with more intensive options, or the quality of the meat produced may not match consumer preference (Ward et al. 1977). Intensified efforts in energy-conservation research on animal production would facilitate the development of more energy-efficient feeding schemes that might counter these deficiencies.

Table 10 - Fossil energy use of low- and high-energy management systems for rearing dairy heifers (adapted from Leach 1975)

Inputs	Low energy		High energy	
	Production units (kg)	Fossil energy (10^3 kcal/animal)	Production units (kg)	Fossil energy (10^3 kcal/animal)
Milk substitute	16	29	16	29
Grass[1]	3,247	769	3,255	1,892
Hay[2]	1,664	1,042	1,145	1,448
Concentrates	628	1,209	628	1,209
Machinery and bedding		447		447
Total fossil energy		3,496		5,025

[1] Grass pasture received 100 kg N/ha in low energy option, 450 kg N/ha in high energy option.
[2] Grass hay received 250 kg N/ha in low energy option, 350 kg N/ha in high energy option.

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Discussion

Marten: In reflecting on dairy farming in New Zealand compared with Minnesota or Wisconsin, energy inputs in New Zealand seem substantially less compared to Northern United States. What would you guess would be the energy budget differences between New Zealand and United States? What ratio?

Heichel: At least a factor advantage of 2-3:1 to New Zealand.

Runge: How is energy efficiency related to profit?

Heichel: Energy is not recognized at its true market value, so it is difficult to relate energy efficiency to profitability. If energy were truly priced, energy costs and profitability would go together.

Syers: Are farmers in the Midwest United States attempting to reduce fossil energy inputs? Has it affected profitability?

Heichel: Yes, farmers are very conscious to lessen their energy costs relating to fossil fuels.

Minson: A feedlot of 350 steers was the most efficient in energy terms. Why do smaller feedlots have a lower efficiency?

Heichel: I believe economics of scale cause larger feedlots to be more efficient than smaller ones.

Burns: Do you perceive a movement back to pastures and longer rotations with legumes in dairy farming on an energy basis?

Heichel: The producer will be the one who decides on whether it is economic to make this shift to more pastoral farming. It is difficult to say that we would revert to the older system.

Marten: Alfalfa/corn silage is presently the basis of much United States farming.

Burns: Dairy farmers like to use grain feed because of reliability of supply.

Helyar: Is the price of store steers/kg higher than finished steers/kg in United States? If so, why?—as it is the opposite in Australia.

Jorgensen: Corn is cheap and so its use is attractive for finishing stock. Relative cheapness and reliability of supply of corn as a stock feed acts as a constraining factor on a move to pastoral farming.

Edaphic Limitations and Soil Nutrient Requirements of Legume-Based Forage Systems in Tropical Areas

K.R. Helyar[1]

Abstract

A brief description of the distribution of soils in the tropics, precedes discussion of the edaphic limitations to pasture legume production imposed by soil moisture and fertility characteristics. With the exception of amelioration of sodic clay soils using calcium sulphate, soil moisture holding characteristics are not easily manipulated. The differences between soils in their available moisture storage capacity and the effect of the storage capacity on dry matter production and species adaptation are discussed. Soil fertility limitations to legume production are usually not absolute but operate through an interaction between the amount and form of applied fertilizer, associated costs, and increases in returns resulting from fertilizer use. It is shown that even though a fertilized legume-based pasture may yield higher profits than an existing grazing system, pasture improvement is unlikely to occur if the 'break-even period' (period for the total cash returns to exceed cash returns to exceed cash outlays) exceeds about 5 years. Thus soil limitations to production from pastures are expressed through both the initial capital inputs (e.g., fertilizer, extra animals, pasture seed), which affect the break-even period, and the long-term productivity and maintenance costs, which control the long-term profitability. Minimizing the initial and/or the maintenance fertilizer requirements is therefore an important means of reducing edaphic limitations to legume-based pasture production. The definition and manipulation of initial phosphorus requirements and of maintenance lime requirements are discussed as examples of approaches to reducing soil limitations to pasture production.

Introduction

Edaphic limitations to the production of legume-based pastures are associated with the capacity of the soil to supply the water and nutrient requirements of the plants. The objective of this paper is to identify edaphic constraints to the production of legume-based pastures on tropical soils. Constraints that may be economically overcome using management techniques developed from research findings are emphasised. Thus the economically manipulable area of soil fertility has received more attention than soil moisture characteristics.

Soils of the Tropics

The approximate proportions of the major soil sub-orders (U.S. Soil Taxonomy) in the tropics are oxisols--22%, aridisols--18%, alfisols--16%, ultisols--11%, inceptisols--8%, entisols--8%, vertisols--2%, mollisols--1%, and mountain areas--12% (Sanchez 1976). Very broadly speaking, fertile young soils and highly weathered soils occur across all tropical areas. The reputation for tropical areas being dominated by highly weathered soils (e.g., oxisols and ultisols) is true for the higher rainfall, old stable land surfaces--essentially the Congo and Amazon basins and surrounding areas. The generalization does not apply to much of India, South East Asia, Australia, and Central America, however, where aridisols, alfisols, inceptisols, entisols, and even vertisols (Australia and India) may be important (Sanchez 1976, Isbell 1978).

Edaphic Limitations to Pasture Production

Soil Moisture

The wide range in the capacity of different soils to store water within the root zone of pasture species has an important influence on the distribution and use of pasture legumes within climatic zones. More drought tolerant, early maturing, and usually lower productivity species are associated with soils of lower available moisture holding capacity (McCown 1973).

Many factors are involved in determining the available moisture holding capacity of the soil profile. These include the root depth by density profile, the moisture held between moisture potentials of -10 and -1,500 k Pa (mainly determined by soil texture, organic matter, and structure) and factors related to infiltration, drainage, and run-off. For example the extent, depth, and stability of cracks in cracking clay soils and the hydraulic conductivity of the B horizon of texture contrast soils (soils with a coarse textured horizon overlying a fine textured horizon) are important determinants of storage capacity (Williams 1983).

Williams (1983) discussed the role of the various factors in determining the profile water store for four major groups of soils with comparable moisture properties. Deep sands have storage capacities between 50 and 150 mm/m depth depending on the fineness of the sand. Uniform and gradational non-swelling earth profiles store around 150 mm/m, but, because of differences in rooting patterns have useable storage of 100-300 mm. Texture contrast profiles with clay B horizons permeable to roots and water usually have available storages in the range 120 to 230 mm, whilst those with sodic clay B horizons resistant to root and water penetration often have available storage of only 25 to 100 mm. Cracking clay soils vary greatly in their effective storage capacity from 35 to 60 mm (thin self-mulching horizon, unstable structure) to 100 to 200 mm (deeper self-mulching horizon, smaller more stable peds) or to 180 to 250 mm (many black earths with deep and well developed structure). Exceptional black earths may store up to 330 mm of available water. In addition, rooting depth, and hence soil water storage, in the more strongly weathered oxisols and ultisols of the tropics, may be restricted by high soluble aluminium levels (Soares et al. 1975) as well as by soil strength effects.

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Increases in the available soil water store affect both species adaptation and production of dry matter per hectare by extending the growing season and by reducing moisture stress during dry periods in the growing season (McCown 1973). The potential extension of the growing season for soils with moisture stores between 50 and 300 mm can be assessed by dividing the storage capacity by potential evapotranspiration rates (Ep values). Ep values in the tropical savanna regions are typically 2-4 mm/day in the wet season and 4-10 mm/day in the dry season (Nix 1983). Assuming an Ep value at the end of the wet season of 6 mm/day, then growth can be sustained for 4 to 50 days into the dry season on soils with storage capacities of 25 to 300 mm. McCown (1973) found the pasture growing season varied between soils by 0 to 22 days for soils of 80 to 180 mm storage, depending on the seasonal rainfall pattern.

Some areas in the tropics and sub-tropics have a non-seasonal rainfall pattern coupled with annual average levels less than 1,000 mm/year. Examples are central Queensland, the northern tip of South America, north-east Mexico, and areas south of the Amazon basin (Nix 1983). In these regions, dry periods can occur at any time of year, so the soil moisture storage capacity can be critical to plant growth at any time of year. Such soils are thus relatively more important in these areas than in areas where the soil moisture store is mainly used to extend the growing season.

For the above reasons the capacity of the soil to store moisture in a form available to the plant has important effects on both the amount of dry matter produced and on the species and varieties that can be grown. However, apart from minimizing soil erosion and applying gypsum to sodic clay soils to increase infiltration and hence soil moisture storage (Williams 1983), manipulation of soil moisture storage level is difficult.

Soil Fertility

Interactions Between Fertilizer Requirements, Profits, and Edaphic Limitations. Studies of the economics of pasture improvement with introduced legumes and/or grasses (Pearse 1963, Beck et al. 1982, Vere and Campbell 1984) have demonstrated that: (i) it may be 3 to 8 years before annual receipts exceed cash expenses; (ii) the break-even period for accumulated receipts to exceed accumulated expenses plus interest may be 6 to 15 years; and (iii) these periods are sensitive to the amount of capital borrowed, any tax savings, the interest rate, and the rate of increase in pasture productivity. Pearse (1963) concluded that, where capital is available, there is generally a long period before receipts exceed expenses and furthermore that "pasture improvement from savings will be a long, discouraging task, with the time before receipts exceed expenses being far distant." This means that although an established improved pasture system may be more profitable and productive than the native pasture, if the costs and returns are such that the break-even period is long, pasture improvement is unlikely to occur.

The contribution of the initial fertilizer costs to the capital required to establish grass/legume pastures therefore decreases the chance of pasture development occurring. For example, of the 42 million hectares suitable for improved pastures in Queensland (Weston et al. 1981), only 3.2 million hectares had been developed by 1980. Seventy-two percent of the improved area was on land requiring no fertilizer, 22% on high-productivity land (carrying capacity exceeding 2 steers/hectare) requiring fertilizer, and only 5% on low-productivity land requiring fertilizer (Scattini 1981).

In southern Australia, large areas of legume-based pastures of low productivity (3-8 sheep/hectare) have been established, but usually in rotation with cereal crops. In this case the pastures are sown under the last crop and utilize the phosphate fertilizer residues from the cropping phase (Scott 1973, Southwood et al. 1976). Thus both the pasture establishment and fertilizer costs are minimized, allowing improved pasture development in a low-productivity environment. Comparable rotations of crops such as sorghum, cassava, and soybeans with short-term improved pastures in lower productivity (0.4 to 1.0 steers/hectare) tropical areas may stimulate pasture improvement in these areas (Arndt and McIntyre 1963, Sanchez and Salinas 1981).

It is tempting to suggest that once the initial capital investment in pasture establishment has been made, then maintenance of the pasture would be relatively insensitive to fertilizer costs. It has been argued theoretically (Godden and Helyar 1980) and demonstrated in practice (Pulsford 1980, Bennett 1981), however, that maintenance fertilizer rates are highly sensitive to the ratio of product-to-fertilizer prices. Thus the area of improved pastures may decline in periods of unfavourable cost/price ratios (Scattini 1981).

Minimizing Initial and Maintenance Fertilizer Requirements. Wide ranging reviews of the mineralogy of tropical soils, and the nutrition and fertilizer requirements of tropical and sub-tropical pastures, have been recently published (Bornemisza and Alvarado 1975, Sanchez 1976, Andrew and Kamprath 1978, Sanchez and Salinas 1981). Others have given details on the research methodology used to investigate fertility problems in a new environment (Andrew and Fergus 1976, Sanchez and Salinas 1981).

It seems pointless to reiterate the findings of these authors. Rather, the means of minimizing the initial (capital) and long-term (maintenance) investments in soil fertility will be considered. As argued above, achievement of either of these aims will help to overcome soil restrictions to pasture improvement. Greater fertilizer capital requirements are associated with: (i) higher plant external requirements as affected by root morphology or the plant internal requirements (Godwin and Wilson 1976) or mycorrhizal associations (Abbott and Robson 1982); (ii) higher soil buffer capacities for the nutrient, affected mainly by the adsorption-desorption properties of the soil for the nutrient (Helyar and Godden 1976); and (iii) lower dissolution rates for the fertilizer (e.g., rock phosphate versus superphosphate).

Maintenance fertilizer rates, on the other hand, are controlled by a different set of factors; those factors which affect nutrient losses from the biologically cycling pool--product removal, erosion and runoff, leaching, volatilization, and long-term near linear rates of accumulation of nutrient in slowly cycling inorganic and organic forms. The latter 'loss' is included in the maintenance requirements because from the point of view of long-term investments (10 to 20 years), accumulation of the slowly cycling nutrients has little effect on production.

Initial phosphate requirements and maintenance lime ($CaCO_3$) requirements are discussed as examples of applications of these principles.

Example (a).--Initial phosphorus requirements for deficient soils vary between 20 and 200 kg P/ha (Fox 1978). For soluble P sources the main factor causing the variation is the soil PBC (phosphate buffer capacity in the units μg P sorbed/g soil between 0.25 and 0.35 μg solution P/ml after 17 hours shaking). In general, fertilizer requirements are >80, 50-80, and 20-50 kg P/ha for P-deficient soils in the PBC ranges >100, 30-100, and 0-30 respectively (Fox 1978, Kerridge 1978, Sanchez and Salinas 1981, Probert 1983). Most Australian soils (Helyar and Spencer 1977, Probert 1983), and probably most soils elsewhere in the tropics, are in the last category. Important exceptions are the high PBC oxisols and ultisols with high exchangeable Al levels and reasonably high clay contents, and some inceptisols derived from volcanic ash (andepts) with very high surface areas (Sanchez 1976, Fox 1978).

Attempts to manipulate soil PBC levels using competing anions, such as silicate, and organic matter have met with little success. Silicate treatments are generally too expensive (Sanchez and Salinas 1981) and organic matter effects are not clear cut (Lopez-Hernandez and Burnham 1974). The only viable scope for manipulation appears to be the use of lime and time to precipitate soluble Al and subsequently crystallise the solid, thus reducing its reactivity with phosphate (Pierre and Browning 1935, Smyth and Sanchez 1980, Sanchez and Salinas 1981). In the absence of exchangeable aluminium, liming effects are unlikely to be important.

Changing the external P requirements of the plant is a more practical means of manipulating initial P requirements. Legume species and varieties (Ozanne et al. 1969, Ozanne et al. 1976, Jones 1974, Barrow 1975, Godwin and Wilson 1976) and legume/mycorrhizal associations (Bowen and Bevege 1976, Abbott and Robson 1982) have been widely studied in recent years. The ability of legumes such as _Stylosanthes humilis_ to establish and persist on phosphorus-deficient soils (Winks 1973, Shaw and Andrew 1979) has meant the initial P requirements are little above maintenance rates.

For P-efficient species to be valuable in reducing fertilizer requirements they must be efficient in terms of P required/quantity of dry matter produced--not per relative yield. Some of the most efficient species in relative yield terms also have low maximum yield potentials (Jones 1974, Godwin 1981). A further consideration for species that achieve low external requirements by having low internal P requirements is whether the plant P level is sufficient for the animal (Norton 1982).

The third variable affecting initial requirements is fertilizer solubility; initial requirements increasing with decreased solubility (Arndt and McIntyre 1963, Kerridge 1978, Sanchez and Salinas 1981). Rock phosphates vary in their solubility with composition, the fineness of grinding, and soil acidity, but few sources approach the solubility of superphosphate (Sanchez and Salinas 1981). Thus unless decreases in fertilizer costs with solubility are sufficient to balance the increased initial fertilizer requirements, greater capital costs will be incurred using less soluble sources. Sanchez and Salinas (1981) have discussed the role of mixtures.

The options available for minimizing the initial phosphate requirements of a legume-based pasture are to lime the soil to eliminate exchangeable aluminium, to use plant and plant mycorrhizal associations with the lowest external phosphate requirements, and to utilize highly soluble phosphate sources.

Example (b).--Maintenance $CaCO_3$ (lime) applications are required to maintain the soil pH at a desired level (depending on the plant grown or other factors) once that pH has been established. In contrast to nutrient elements where maintenance requirements are only needed to balance nutrient losses, maintenance lime requirements need to balance both the addition of acids to the system and losses of alkaline compounds (e.g., Bronsted-Lowry conjugate bases such as organic and inorganic weak acid anions) from the system.

Maintenance lime requirements can be defined by monitoring the soil pH and estimating the lime required using a lime requirement test (e.g., Kamprath 1970). However, if our aim is to reduce maintenance lime requirements, the causes of soil acidification and their manipulation need to be studied.

Various authors have attributed soil acidification under legume-based pastures to organic acid accumulation (Williams 1980), to the leaching of neutral salt cations such as Ca, Mg, K (e.g., Freitas and Raij 1975), and to acid production resulting from transformations of nitrogen between various forms (Pierre and Banwart 1973, Nyatsanga and Pierre 1973). In a review of the role of nitrogen cycling in soil acidification (Helyar 1976), it was argued that the degree of acidification of some legume-based pasture ecosystems depended largely on the form nitrogen enters and leaves the system and on the loss of Bronsted-Lowry bases from the system. The point of practical importance is that the fluxes of nitrogen and bases to and from the system are under a degree of management control. Two examples serve to illustrate how management can be used to minimize soil acidification rates.

Firstly, there is a strong contrast between the soil pH trends following clearing rainforest by the slash-and-burn technique (pH rises before falling

Table 1 - Soil acidification rates in different pasture systems

System	Fertilizer treatment (kg/ha/yr)	Weeks <0.4	Moisture[1] Mean Annual	Moisture[1] C.V. of weekly means	Stocking rate (hd/ha)	Soil acidification rate (Δ pH/yr)	Estimated $CaCO_3$ for Δ pH = 0 (kg/ha/yr)
Subterranean clover/ phalaris or volunteer spp. Improved/unimproved contrasts after 20-50 years (ultisols & alfisols)[2]	Superphosphate = [3]100	22	0.54	46.5	(Sheep) 5-10	-0.05	250
White clover/Axonopus, Paspalum pasture, 9-yr grazing experiment, Grafton (Ultisol)[4]	0	9	.60	27.7	(Steers) 1.7-3.3	.0	0
	[3]125					- .010	50
	250					- .020	100
						- .027	135
White clover /kikuyu, 8-yr grazing experiment, Wollongbar (oxisol) (basal P & K fertilizer)	NH_4NO_3	0	.89	15.9	(Steers)		
	0N[3]				2.2-4.9	.0	0
	125				3.3-7.4	.0	0
	[5]336				4.9	- .006	30
					7.4	- .021	105
					11.1	- .033	165
	690				7.4-16.1	- .093	456
	$(NH_4)_2SO_4$				(Cows)		
	336				2.5-5	- .158	790

[1]Calculated according to Fitzpatrick and Nix (1970), assuming an available soil water store of 100 mm.
[2]Williams and Donald (1957), Simon and Flemons (1970), Williams (1980).
[3]Supplied near adequate phosphate in this environment.
[4]Mears and Havilah (unpublished).
[5]Mears and Humphreys (1974), Colman and Mears (unpublished), Awad and Edwards (1977).

slowly) or by bulldozing (rapid, permanent drop in soil pH) (Sanchez and Salinas 1981). With the slash-and-burn technique, large amounts of nitrogen are presumably lost via the non-acidifying volatilization pathway, whilst in the bulldozed treatment the acidifying nitrification and nitrate leaching pathway is likely. In addition the alkaline oxidation of organic anions occurs rapidly in the slash-and-burn process, whilst large amounts of organic anions are removed by bulldozing.

Secondly, the causes, magnitude, and means of controlling soil acidification rates can be assessed from long-term soil pH trend data for soils supporting pastures (table 1). Comparison of the soil acidification rates for legume-based pastures supplied with near adequate phosphate indicates acidification rates increase with more seasonal rainfall patterns (contrast the Wollongbar, Grafton, and Southern Tablelands data). Higher acidification rates can also occur with increases in superphosphate and hence nitrogen fixation rates (Grafton site), increases in the nitrogen rate or stocking rate (Wollongbar site), and the change from ammonium nitrate to ammonium sulphate fertilizer (Wollongbar site). These effects can be explained as effects of the treatments and environments on nitrate leaching (Helyar 1976). Higher levels of nitrate leaching and acidification are associated with: (i) longer dry seasons that allow nitrate accumulation then leaching from the soil (Simpson 1962, Wetselaar 1962); (ii) high stocking rates, leading to reduced plant uptake of soil nitrate, leaving it vulnerable to leaching; (iii) increased superphosphate rates that stimulate nitrogen fixation and nitrate accumulation in dry periods, followed by nitrate leaching by subsequent rainfall; and (iv) increases in acid production during nitrification as the ammonium ratio in the N-fertilizer increases (Wolcott et al. 1965).

These examples show that management systems aimed at minimizing soil nitrate accumulation and leaching and at minimizing losses of basic materials from the ecosystem are consistent with minimum maintenance lime requirements. Continuous plant absorption of nitrate, conservative stocking rates, minimal use of physical or chemical fallows, and minimal use of ammonium fertilizers (nitrate fertilizers can lead to increased soil pH) and minimal removal of basic materials are management options. The degree to which these management techniques can be used to minimize acidification needs investigation in various agricultural ecosystems.

Research Priorities

It is concluded that minimizing the edaphic limitations to legume growth expressed through soil infertility can be achieved by minimizing both the capital and maintenance fertilizer inputs. Research designed to achieve this aim should measure the soil

capacity and nutrient loss factors involved for a given nutrient and investigate practical means of manipulating them. It is important to recognise that measurement of gradual nutrient loss processes requires long-term experiments. Well designed and extensively monitored long-term experiments are particularly important for fertilizers such as phosphate and lime with long-term residual effects. These experiments must be repeated at enough sites to enable quantitative definition of the environmental and management factors having important effects on maintenance fertilizer requirements.

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Discussion

Minson: Do you think studies are sufficiently long-term to assess persistence of species, which I consider very important? This is a real problem--it is important, yet few long-term studies are pursued.

Helyar: Rapid processes are probably assessed satisfactorily with short-term experiments, but slow processes require longer term studies. Long-term experiments are thus particularly important to define the residual effects of phosphate and soil acidification rates.

Brougham: The situation in New Zealand appears to be better than in Australia.

Lancashire: I have surveyed N.Z. studies with perennial species, including evaluation of persistency, and the average was only 3 years.

Syers: In New Zealand there are a number of long-term trials at several sites.

Brougham: Pasture development is a long-term process and this is recognized by administrators in New Zealand.

Runge: We have a problem of short-term research in Texas, United States. Commercial firms have been approached to extend length of trials.

Keeney: In Wisconsin we have a panel of three industry people and three farmers to look at length of trials where a fertilizer industry levy is funding research. However, it is still difficult to get funding for long-term trials. In Wisconsin we have a check-off (levy) of 10¢/t on fertilizer.

Edaphic Limitations and Soil Nutrient Requirements of Legume-Based Forage Systems in Temperate Regions of New Zealand

Annette C. Richardson and J. Keith Syers[1]

Abstract

The potential contribution of forage legumes to pasture systems is often constrained by edaphic and soil nutrient limitations. Effects of three soil factors (temperature, water, and acidity) on the ability of forage legumes to establish, persist, and fix N in New Zealand pastures are reviewed. Although several major and minor nutrients are important for the establishment and persistence of forage legumes, five appear to be of particular economic significance; these are N, P, S, K, and Mo. Further research is required to better define the edaphic limitations of legume cultivars and species and to find more efficient ways of meeting nutrient requirements.

Introduction

Forage legumes are an integral component of most animal production systems in New Zealand. However, their full production potential is frequently constrained by edaphic and soil nutrient limitations.

Climatic factors have a strong influence on the distribution of legumes, partly through their influence on soil temperature and soil moisture. Even in areas where climate and soil physical characteristics are suitable for legume growth, soil acidity may limit legumes. In addition, nutrient limitations can be a major constraint to production, and fertilizers are routinely used to stimulate legume growth.

This brief review considers edaphic limitations and the dominant soil nutrient requirements of temperate forage legumes, with particular emphasis on New Zealand and on white clover (*Trifolium repens* L.).

Edaphic Limitations

Soil Temperature

Temperature in the root zone has a strong influence on the ability of forage legumes to establish, persist, and fix nitrogen (N) in pastoral systems.

The percentage and rate of germination of legume seed increase with an increase in soil temperature, up to 20°C (McWilliam et al. 1970). With increasing soil temperature above 20°C, germination declines due to related factors such as decreasing soil moisture (Musgrave 1977). Even near freezing point, germination may still occur slowly (Scott and Hanson 1977). In fact, successful establishment of legumes often relies upon sowing seed between extremes of soil temperature and moisture.

The shoots of temperate legume species will grow at above-ground temperatures of between 5° and 35°C, with an optimum of 20°-25°C (McWilliam 1978). However, Davidson (1969) demonstrated that maximum root production for white clover occurred at 7.5°C below the optimum soil temperature for shoot growth.

The seasonality of forage legume production is strongly influenced by temperature. In particular, the dominance of grass species in mixed pasture between autumn and spring is aided by their greater tolerance of cool conditions. Forage legumes are restricted in the South Island high country because of low temperatures and frosts, although some legume species, e.g., alsike (*T. hybridum* L.) and Caucasian (*T. ambiguum*) clovers are better adapted to cool conditions (Scott 1979).

Processes involved in symbiotic N fixation are highly temperature dependent. The effectiveness of infection with rhizobia and nodulation increases between 10° and 30°C (Roughley et al. 1970). The minimum temperature required for infection is greater than that for nodule development and N fixation (Hoglund 1979). Poor nodulation may explain the inability of pasture legumes to establish under cool conditions. However, variation exists in both white clover and *Rhizobium trifolii* in ability to nodulate and fix N at low temperature.

Increases in nodule volume appear to compensate for any decrease in N fixation by established rhizobia caused by low temperature (Smith and Bowen 1979). However, Pate (1977) found that N transfer between nodules and the host plant may be limiting under cold conditions.

Soil Water

Soil water availability has a large influence on pasture growth. It has been estimated that, during summer and autumn, approximately 3 million hectares of agricultural land in New Zealand suffer from plant-limiting soil-water deficits (Williams et al. 1978); about one-eighth of this area has potential for irrigation. Significantly, drainage and irrigation are generally limited to regions where legumes are already well established.

Establishment of legume seed is often difficult on hill sites because of conflicting soil temperature and water conditions. As the soil warms in spring it also dries, limiting the period when legume sowings are successful. On semi-arid tussock land in the South Island only 0.1%-0.7% of coated legume seed survives in most years (Clifford 1975).

Investigations by Evans (1978) showed that lucerne (*Medicago sativa* L.) was able to extract water from 210 cm in a sandy loam, whereas other common pasture and crop species were limited to 130 cm, with a high production of roots being located in the top 20 cm. Lucerne exploited water in the profile uniformly, whereas other species initially depleted surface resources before tapping water at depth.

On fairly substantial areas of coastal sands in New Zealand, pasture legumes are restricted through seasonal drought and waterlogging. Trials by Rumball (1978) in the southern North Island showed

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that lucerne was superior to red clover (T. pratense L.) and white clover at both extremes of soil water content.

Immature lucerne plants are extremely vulnerable to dry conditions before taproot development is complete. On dry pumice soils in New Zealand, McQueen and Baars (1980) concluded that lucerne was economically inferior to drought-tolerant grasses and improved grazing of mixed pasture, because of high establishment costs, poor winter production, and susceptibility to pests and diseases.

Water stress and waterlogging also depress N fixation. Water stress depresses the activity of existing nodules and reduces nodulation. Nodules become stressed when the water supply is insufficient to export fixation products and compensate for water losses to the soil (Pate 1976). Sprent (1976) has shown that nodule number and size are altered in flooded soil. Oxygen deficiency, caused by surplus soil water, depresses the fixation of atmospheric N (Mague and Burris 1972).

It is claimed that forage legumes, especially perennial clovers, can survive up to 20 days of flooding (Boswell 1979). However, tolerance of high soil water content decreases with an increase in temperature (Thompson and Fick 1981).

Soil Acidity

Virtually all N.Z. soils are naturally acidic. For example, of the 5.2 million ha of tussock grasslands, about 1.8 million have pH values of 5.0-5.2, and a further 1 million ha have pH values of below 5.0 (Scott and Mills 1981).

In general, temperate legumes, particularly lucerne, are less tolerant of acid soils than grasses. However, it is with the survival and growth of rhizobia, rather than with the host legume, that soil acidity has its greatest effect. Hydrogen ions in the soil solution can adversely affect rhizobia and legume growth, but it is the effects of soil acidity on the availability of other elements which are the most detrimental.

Differences exist among legumes in their tolerance of soil acidity, as demonstrated in New Zealand by Davis (1981) and Haynes and Ludecke (1981).

The concentrations of aluminium (Al) and manganese (Mn) ions can increase to toxic levels at low pH on low fertility tussock grasslands. Under these conditions, Lowther (1980) found that white clover was restricted by Al, but not Mn toxicity. Although plants show a similar sensitivity to both elements (Robson and Loneragan 1978), there is little evidence that Mn toxicity is a major limiting factor in N.Z. pastures (Smith and Edmeades 1983).

There is a strong deleterious interaction between the concentration of Al and phosphorus (P) availability in acid soils. In a pot trial conducted by Nordmeyer and Davis (1977) it was found that increasing P applications decreased the Al content in white clover and to a very much lower extent in lotus (Lotus pedunculatus Cav.). Similar results have been reported by Bouton et al. 1981 with lucerne. Under field conditions, Scott and Lowther (1980) found that white clover and lotus were unable to take up P where soil solution Al concentrations were high, even though P was readily available in the soil. The reduced availability of P to legumes in acid soils has considerable economic implications.

Deficiencies of calcium (Ca), magnesium (Mg), and molybdenum (Mo) can restrict forage legumes in acid, temperate soils. Although Ca does not appear to restrict plants in local soils, Dorafaeff and McNaught (1962) showed a pasture response to Mg application on pumice soils. Under acid conditions, low Ca and Mg can restrict the survival of rhizobia and affect legume nodulation (Robson and Loneragan 1978). Molybdenum deficiency commonly limits N fixation in acid soils, and this is discussed below.

Soil Nutrients

A large number of major and minor nutrients are important for the establishment and persistence of forage legumes. Of these, nitrogen (N), P, sulphur (S), potassium (K), and Mo are probably the most economically significant in New Zealand.

Nitrogen

Some rather complex ecological and management factors influence the N economy of mixed pastures, associations of grasses and legumes being basically unstable. During the development of grazed pasture, legumes are initially dominant owing to the low availability of soil N (Brougham et al. 1978). As soil N levels increase, through biological fixation and cycling, grasses become more competitive and begin to dominate a sward. The greater resilience of grasses to climatic and edaphic limitations fosters the decline of legumes in an association (Suckling 1975). In a natural cycle, grasses would deplete N levels in the soil until legumes re-established their dominance. However, through nutrient inputs (particularly P and S) and by grazing management, pasture can be maintained with sufficient legumes to supply N and with a large proportion of grasses for high production. Such a model depicting the relationship between N fixation, legume growth, and soil N availability has recently been proposed by Hoglund and Brock (1982).

Phosphorus

New Zealand is one of the highest per capita users of fertilizer P in the world, and large quantities, principally as single superphosphate, are applied annually to stimulate legume growth and N fixation. The poor competitive ability of white clover for P, relative to grasses, often limits the benefits of P application to mixed pastures. Jackman and Mouat (1972) showed that the roots of grass and white clover compete directly for phosphate ions. Generally, grasses have longer, thinner, and more finely branched root systems than clovers (Evans 1977). Therefore, the surface area of the root hair cylinder and volume of soil exploited by grass root hairs are several times greater than those of clovers. As pointed out by Brougham et al. (1978), such characteristics place clovers at a disadvantage

in terms of effectively exploring a particular volume of soil and in recovering nutrients, such as P, which diffuse over very short distances (Lewis and Quirk 1967).

In experiments reported by Barrow (1975), the uptake of P per unit of root length was higher for ryegrass than for subterranean clover (T. subterranean L.). This was attributed to root morphology and the ability of ryegrass to lower the concentration of P around the root. By maintaining a steep concentration gradient between the root surface and the soil solution, diffusive movement of P and the proportion of P available to ryegrass increased. The advantage to ryegrass reported by Barrow, was particularly apparent with soils which had a capacity to sorb large amounts of P.

In a study at the Grassland Research Institute, UK, Syers et al. (1984) showed that irrigation resulted in a more even distribution of root activity with depth for both grasses and white clover. Lateral exploitation of soil P was also increased, pointing to an interesting interaction between soil moisture and P uptake. In the absence of irrigation, grasses were more effective in exploiting soil P reserves. With irrigation the relative ability of white clover to recover P was enhanced. This was reflected in both root activity (determined using ^{32}P) and herbage P concentration.

Recent N.Z. work indicates that P requirements are greater for N fixation than for legume growth. Hart et al. (1981) have shown that total P concentrations in white clover and lotus were always higher in symbiotic plants than when plants were assimilating mineral N.

Recent results (Mackay et al. 1984) also suggest that certain reactive phosphate rock materials, which contain some calcium carbonate, can stimulate clover growth more than superphosphate. The extent to which the release of P over a longer time, and/or a more favourable pH environment for rhizobia, is responsible for the better growth of clover is not clear.

Sulphur

Sulphur reserves in most N.Z. soils are considered to be inadequate for satisfactory legume growth (Walker and Gregg 1975). This is particularly important where leaching is intense, because of high rainfall and the coarse texture of the soil, and in the early stages of land development when S is immobilised extensively in soil organic matter. In more developed situations, the requirement of legumes for S has often been masked by the application of single superphosphate to pastures. However, some legume-based pastures are more deficient in S than in P (During 1972). With increasing use of alternative sources of P in New Zealand, S limitations are likely to become more apparent (Gregg and Syers 1983).

Deficiencies of N and S can occur simultaneously in pasture legumes. A limitation of plant-available S reduces N fixation directly through impaired production of nitrogenase enzyme (Blair 1979), and indirectly by grass domination of the sward.

Sulphur application to deficient plants has been shown (McNaught and Chrisstoffels 1961) to stimulate nodulation and N fixation. Over the range of plant growth response, both N and S levels in legume tissue increased simultaneously.

Grasses are usually more effective than clovers in S uptake. Walker and Adams (1958) concluded that 98% of the S mineralised on an S-deficient soil was used by grasses in a mixed pasture. Sheard et al. (1978) reported that ryegrass absorbed more S from a surface application of ^{35}S-labelled gypsum than white clover. In many N.Z. pastures, herbage S concentrations in white clover are not only lower than in grasses but are only marginally sufficient (Metson 1973).

Sulphate is retained less strongly and moves more readily in soils than phosphate (Marsh et al. 1983). Consequently, it is not surprising that the generally deeper-rooting grasses are better able to remove part of the sulphate which accumulates in the subsoil. This is unlikely to be the case with phosphate, because of its very restricted movement within the soil.

There is increasing evidence to suggest that fertilizers which supply S in the sulphate form may not be the most appropriate for some soils in New Zealand. Elemental S supplies sulphate-S over an extended period of time but the relationship between frequency of application and particle size is not well understood.

Potassium

Under N.Z. conditions, K deficiencies in forage legumes are less common than P and S deficiencies. However, some soils contain low amounts of plant-available K, and responses to fertilizer K are obtainable (During 1972). High-producing pastures used for dairying often require large applications of K to balance losses. Leaching losses of soil and fertilizer K from some soils limit the availability of this element for legume growth. Use of highly soluble K fertilizers further increases the problem.

As with other nutrients, pasture species compete for plant-available K in the soil. Potassium-deficient pastures are usually grass dominant, and an application of K increases the legume component. Although grasses and forage legumes require similar tissue concentrations of K for maximum growth (Asher and Ozanne 1967), grasses are less sensitive to deficiency and have a greater capacity for absorption. At high concentrations of K, Dunlop et al. (1979) found that excised ryegrass roots had a specific absorption of K which was twice that shown by excised white clover roots. Extrapolating this work to concentrations found in K-deficient soils, they suggested a five-fold difference in absorption rate between ryegrass and white clover.

Molybdenum

Molybdenum is an essential component of nitrogenase and nitrate reductase enzymes involved in N fixation and N metabolism, respectively (Mengel and Kirkby 1982). Only trace amounts are required for plant growth, but legumes are particularly sensitive to deficiencies of Mo.

Molybdenum deficiency is widespread in New Zealand, especially in the South Island. At low soil pH, Mo availability decreases in a similar manner to that of phosphate. Liming can correct Mo deficiency, although application of Mo fertilizers may be less costly in some situations (During 1972).

Growth responses of forage legumes to surprisingly high rates of lime and molybdenum were reported by Lobb (1953). On a wide range of Otago soils, application of Mo increased soil N status following increased legume growth.

Although the areas of serious Mo deficiency have probably been recognised, the extent to which a marginal deficiency of this element limits legume growth, particularly in N.Z. hill country, is unknown.

Research Needs

A need is seen to better understand the edaphic limitations of forage legume species and cultivars so that high production from legume-based pastures can be achieved more effectively.

Selection for resistance to water stress and tolerance of low temperature and soil acidity are clearly important, but progress often appears to be slow.

Our understanding of the nutrient requirements of forage legumes appears to be reasonably good, but interactions between nutrients are less well understood. In particular, the interaction between availability of soil and fertilizer P and soil pH and the effects on legume growth, are poorly defined.

Continued investigation into the efficiency of fertilizer use should be given high priority because of its direct and substantial implications to the economics of pastoral farming.

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Discussion

Collins: Is there genetic variability in tolerance to soil exchangeable Mn?

Syers: Yes. Good work has been done in Australia on this topic but I am unaware of similar N.Z. work.

Steele: There is limited evidence for variation in Mn tolerance from work at Ruakura (MAF, Hamilton, N.Z.).

Marten: Why is it that in the United States we are taught that lucerne will not grow at pH below 6.5, whereas it appears to grow in New Zealand at pH as low as 5.5?

Syers: If phosphate is adequate and aluminium toxicity is not a problem, lucerne should grow well at lower pH's than 6.5. This is confirmed in Georgia, United States, where lucerne has been grown successfully at pH 6 and even down to pH 5.5.

Heichel: The Minnesota group have found strains of Rhizobium meliloti that differ in their effectiveness on lucerne, depending on pH.

Lowther: A survey of pH/aluminium relationships in the Mackenzie Basin is being carried out at Tara Hills by Malcolm Douglas. Low pH is only a problem at the establishment and inoculation stage, and this can be overcome, in time, by using lime-pelleted, inoculated seed.

Syers: What pH values are being found?

Lowther: pH values of 5.3 are supporting 20-year-old lucerne stands.

Reed: A survey was carried out in Southwest Victoria. In acidic soils supporting lucerne, it was found that the subsoils were much nearer neutral.

Syers: Perhaps plants were rooting largely in the subsoil.

Brougham: What edaphic factors limit white clover growth in N.Z. hill country?

Syers: Climatic limitations and low availability of nutrients are the key factors. Low winter temperatures and summer drought are important. Soil pH values of 4.6-5.0 in the South Island and 5.0-5.4 in the North Island are often limiting. The challenge is to get limiting nutrients into the system in the most economical way.

Unknown: Are you aware of variation in tolerance to soil salinity?

Syers: Not in New Zealand, because salinity is a minor problem. Less than 1% of our soils are affected by salinity.

Edaphic Limitations and Soil Nutrient Requirements of Legume-Based Forage Systems in the Temperate United States

Dennis Keeney[1]

Abstract

The soil factors (pH, Al, Mn, salinity) affecting the distribution and yield of temperate forage legumes in the United States and the nutrient needs of these legumes are reviewed. No single factor or nutrient deficiency restricts legume distribution, but drainage, pH (Al toxicity), and the level of available P or K are most often limiting yield or stand survivability. Research is needed to improve the capability to predict nutrient needs, and to identify and correct growth-limiting factors for forage legumes on marginal lands.

Introduction

Mannetje et al. (1980) emphasize that the Leguminosae are found in virtually all types of vegetation and climates and in most soils. Legumes grow in acid (pH<4) to alkaline soils; *Rhizobium* are similarly adapted, ranging from slow-growing alkaline-producing strains that nodulate effectively the primitive tropical legumes to faster growing acid-producing strains. Agronomists, through plant introduction and breeding, have produced legumes for a wide range of edaphic conditions.

Mays et al. (1980) estimate that there are at least 30 legume species used for forage in the United States, the most important (particularly in the North Central and Western regions) is alfalfa (*Medicago sativa* L.) or lucerne. Wisconsin is the leading producer, with 1.7 million ha of alfalfa (hay, green chop, and silage). The average yield in 1981 was 7.4 t ha^{-1}, but many counties average 9 to 12 t ha^{-1} (Wisconsin Department of Agriculture, Trade and Consumer Protection 1982). Research yields of 18 to 22 t ha^{-1} are possible, and top Wisconsin farmers product 11 to 18 t ha^{-1}. In the Western United States, on irrigated fields, yields are in the range of 30 to 65 t ha^{-1} (Rohweder 1982). Other important temperate U.S. legumes are red clover (*Trifolium pratense* L.), sweetclover (*Melilotus*), white clover (*Trifolium repens* L.), and birdsfoot trefoil (*Lotus corniculatus*). Lespedezas, as both annuals [Korean (*L. stipulacea*) and *L. striata*] and the perennial sericea (*L. cuneata*) are important in the Southeastern United States, as are the winter annuals crimson clover (*Trifolium incarnatum* L.) and arrowleaf clover (*Trifolium vesiculosum*) (for more complete information, see Heath et al. 1973). It is beyond the scope of this chapter to consider each of these in detail; table 1 attempts to briefly summarize the distribution of these species and their edaphic adaptation.

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Edaphic Limitations

pH, Aluminum, and Manganese Toxicity

One striking feature of table 1 is that U.S. forage legumes in general are not adapted to acid soils. While the reasons for this are complex and involve, among other things, numerous nutrient-pH interactions, the primary reason for a positive legume yield response to increasing pH is a decrease in Al and perhaps Mn toxicity to plants and to rhizobia (Jackson 1967, Pearson and Hoveland 1974, Robson and Loneragan 1978). In the North Central and Northeast United States, poor soil drainage is perhaps the most important factor affecting alfalfa survivability. In Wisconsin, nearly all of the alfalfa is grown on well-drained to moderately well-drained soils (Wisconsin Statistical Reporting Service 1977, Rohweder 1982).

At soil pH values below about 5.5, Al or Mn toxicity can severely reduce alfalfa growth (Pearson and Hoveland 1974, Brown and Graham 1978). Other workers have recently confirmed that alfalfa yield increases due to liming were related to decreased exchangeable Al (Alley 1981) or Mn (Mahoney et al. 1983). The clovers and birdsfoot trefoil are relatively more tolerant of soil acidity than alfalfa, whereas varietal differences and rhizobia tolerance affect the actual yield responses to lime (Pearson and Hoveland 1974). Recent studies have shown that acidity, along with Ca, Mo, and Co deficiency, can markedly impair the function of established nodules and that rhizobia are more sensitive to acidity than is the host plant (Robson and Loneragan 1978, Munns and Mosse 1980, Mahler 1983).

Legume species adapted to acid soils and showing some tolerance to Al toxicity appear to: (1) have more efficient P uptake and transport mechanisms; (2) decrease acidity of the rhizosphere relative to the soil; and (3) to be more tolerant of high Mn, low Ca and low Mo availability than acid-intolerant species (Robson and Loneragan 1978).

Salinity

High salinity can markedly limit legume growth, although considerable variation in tolerance among and within legume species exists. Salinity appears to affect rhizobia activity more than growth of the host plant (Robson and Loneragan 1978). Alfalfa is one of the most salinity-tolerant pasture legumes (Peterson 1972, Leach 1978), but production, stand establishment, and persistence may be affected by high salinity. Toxic effects due to B, Na, or Cl may also be involved. Francois (1981) found that, while high salinity in the surface soil markedly decreased alfalfa growth, the salinity level in the lower portion of the rooting zone had little effect. Smith and Peterson (1975) noted apparent Cl^{-} toxicity to alfalfa at excessive rates of KCl fertilization (equivalent to 2,030 kg ha^{-1} Cl).

Table 1 - Important forage legumes in the United States (largely from Heath et al. 1973)

Legume	Dominant region	Edaphic requirements
Alfalfa (*Medicago sativa* L.)	Throughout, over 60% in North Central, 23% in West	Near neutral pH, high Ca, P, K required
Red clover (*Trifolium pratense* L.)	North Central and Northeast	pH 6 or greater, high Ca, P required
Sweetclover (*Melilotus*)	Central	pH 6.5 or greater
White clover (*Trifolium repens*)	Eastern	pH 6-7, will not tolerate salinity or high alkalinity
Birdsfoot trefoil (*Lotus corniculatus*)	North Central, Northeast, Far West	Widely adapted, more tolerant of acidity, and low fertility
Lespedezas	Southeast	Will grow on acid, infertile soils, respond to lime, P, and K
Crimson clover (*Trifolium incarnatum* L.)	Southeast	Near neutral soils, high P, K; will tolerate acid soils
Arrowleaf clover (*Trifolium vesiculosum* Savi)	South	Neutral soils, high fertility required

Nutritional Factors

Tissue Analysis

In the past decade, alfalfa yields have increased markedly due to improved varieties and management, requiring a rethinking of many of the earlier fertility recommendations. Relatively less information is available on other hay legumes and even less on pastoral systems. In addition to maximum profitable yields, stand survivability over winter is a major concern in the North Central and Northeast United States.

The major approach to research on nutrient requirements for forages is the classical factorial plot trials with cut-and-carry yield measurements combined with soil and tissue tests. The yield responses are site- and management-specific. However, nutrient removals and tissue concentrations are more widely applicable. Most emphasis has been placed on analysis of tissue collected at about the early-bloom stage, just before commercial harvest; Martin and Matocha (1973) have extensively reviewed the literature on forage plant tissue analysis. They also discuss the principles of plant analysis. The usual means of relating yield to tissue nutrient concentration is either the sufficiency approach (low, sufficient, high) or the critical value approach (the nutrient concentration where a 5% to 10% yield reduction is evident). These approaches have the disadvantage that a given nutrient level may vary widely due to environmental, insect, or disease stress or to deficiency of other nutrients. Most importantly, they vary with variety and plant age.

Sumner (1979) has advanced the Diagnosis and Recommendation Integrated System (DRIS) to overcome these deficiencies. This holistic approach characterizes the yield-determining factors in terms of indices which are derived as comparable functions of yield. Once validly established, DRIS norms should be universally applicable to that crop irrespective of age or cultivar. The system involves gathering a substantial data base, obtaining the mean of every combination of nutrients ratios in the high-yielding population (i.e., N/K, N/P, etc.), and then calculating a DRIS index to give a whole-number ranking indicating degree of deficiency, sufficiency, or excess. This technique is being investigated for alfalfa by Wisconsin researchers (Erickson et al. 1982, Kelling et al. 1983). DRIS norms available to date are given in table 2. Table 3 presents some critical ranges and nutrient removals for alfalfa. Critical values for clovers appear to be similar for most species and are about the same as those for alfalfa given in table 3.

Individual Nutrients

Potassium. Potassium is needed in greatest amounts by most legumes (table 3). Because grasses are able to compete effectively with legumes for soil K (Robson and Loneragan 1978) higher rates of fertilizer K will be needed to maintain a legume in a mixed sward than in a pure stand (Blaser and Kimbrough 1968, Rhykerd and Overdahl 1972, Baylor 1974, Robson and Loneragan 1978). More K is taken up by legumes in warm than in cool environments (Smith 1971), indicating that higher soil-test K levels are needed for optimum growth in cool climates. Potassium availability and soil pH most greatly affect over-winter survival and stand longevity (Blaser and Kimbrough 1968, Griffith 1974), and it is imperative that high available soil K be maintained into the autumn. Potassium is also critical to N fixation (Collins et al. 1983).

Phosphorus. No large contiguous areas of acute P deficiency exist. The low mobility of P in soils offers a large competitive advantage to fine-rooted grasses over taproot legumes, and thus it is imperative that grass-legume mixtures have adequate P to maintain the legume and supply N for the grass (Mays et al. 1980). Further, nodule development and N fixation are dependent on adequate P (Munns and Mosse 1980, Collins et al. 1983). Mycorrhizal associations have been shown to increase P uptake of legumes, particularly at low levels of available P (Munns and Mosse 1980).

Sulfur. Deficiencies of S occur on legumes throughout the United States but are most common on low-organic-matter sandy soils, in areas where atmospheric input is low, and where manure has not been recently applied (Rhykerd and Overdahl 1972, Griffith 1974, Syverud 1983). The combination of higher yields and use of high-analysis, S-free P fertilizers has brought increased attention to S as a major limiting factor in high-yielding legume systems. The prediction of yield response to S fertilizers by testing of soils for available S is more uncertain than for P and K, probably because of the largely ephemeral nature of SO_4 resulting from the high mobility of SO_4-S and inputs of available S from the atmosphere, mineralization of soil organic S, subsoil SO_4-S levels, and inorganic SO_4 sorption-desorption reactions.

In many mixed legume-grass experiments, S deficiency has been associated with grass dominance (Martin and Walker 1966, Robson and Loneragan 1978). Sulfur application has increased alfalfa survival (Leach 1978) and greatly increased forage quality (Jones et al. 1982). It is common for the protein concentration of legumes to increase when S is applied to S-deficient sites (Jones et al. 1982), due both to the close relationship of N and S in protein synthesis and the stimulatory effect of S on N_2 fixation (Collins et al. 1983).

Soil S availability appears to influence the uptake of several other elements by legumes. These include enhancement of the uptake of P and K and depression

Table 2 - DRIS tissue norms and supporting statistics for alfalfa[1]

Plant composition parameter	Norm value[2]	Standard deviation	Variance ratio (S/S_B)
N/P	10.3	1.74	1.78** (0.01)
N/K	1.26	.280	6.46**
S/N	.0779	.0153	.95 (n.s.)
N/Ca	2.46	.630	1.74**
Mg/N	.0855	.0253	3.00**
B/N	.0972	.0320	1.31* (0.05)
P/K	.124	.0244	5.96**
S/P	.771	.181	1.48**
Ca/P	4.34	1.28	2.02**
Mg/P	.924	.335	2.74**
B/P	.972	.378	2.36**
S/K	.0908	.0258	7.68**
Ca/K	.534	.215	5.23**
Mg/K	.113	.0514	9.60**
B/K	.117	.0500	7.48**
Ca/S	5.89	2.15	1.53**
Mg/S	1.21	.356	1.81**
B/S	1.25	.324	2.17**
Mg/Ca	.216	.0581	1.64**
B/Ca	.232	.0823	3.09**
Mg/B	1.03	.404	1.71**

[1]Source: Erickson et al. (1982); based on over 200 values from high yielding (4.4 t ha^{-1} per individual harvest) populations.
[2]Norms calculated for % tissue concentration except B, which is mg $kg^{-1} \times 10^{-2}$.

Table 3 - Critical value concentrations and average nutrient removal by 10 tons (10,000 kg) of alfalfa[1]

Nutrient	Critical Value	Removal
	%	kg 10 t^{-1}
Nitrogen	4-5	400-600
Phosphorus	0.20-0.25	20-30
Potassium	1.5-2.0	150-280
Sulfur	0.20-0.22	20-30
Calcium	1.8	220
Magnesium	0.3	70
	mg kg^{-1}	g 10 t^{-1}
Boron	20	200-400
Manganese	20-30	200-300
Molybdenum	0.5	10-50
Zinc	4-8	100-200
Copper	5	80-150

[1]Largely from Martin and Matocha (1973) using critical and adequate values for whole tops.

in the uptake of B, Mo, and Se (Rhykerd and Overdahl 1972, Westermann and Robbins 1974, Gupta and MacLeod 1975).

Calcium and Magnesium. Calcium and Mg are rarely limiting to legume growth if the soil pH has been increased by use of dolomitic limestone (Griffith 1974). High K or Ca can depress Mg uptake, and high K or Mg can lower Ca uptake (Griffith 1974, Gross and Jung 1981), but alfalfa is apparently tolerant of an extremely wide range of Ca and Mg (Simson et al. 1979). Jones et al. (1977) found that subclover grown on extremely impoverished serpentine soils responded to Ca additions after P, K, and S were in sufficient supply. Calcium and Mg have marked effects on nodule formation and function and rhizobia growth (Robson and Loneragan 1978).

Minor Elements. The N-fixing legume symbiosis places higher demands on Mo, Co, B, Cu, and Zn relative to other plants. Of these, B deficiency is perhaps most often noted, especially with alfalfa, and soil B availability is difficult to evaluate (Murphy and Walsh 1972, Rhykerd and Overdahl 1972, Griffith 1974). Copper deficiencies in the United States with alfalfa have been noted on organic soils and weathered sandy soils (Murphy and Walsh 1972) and on extremely Cu-deficient soils; they can be accentuated by liming (Brown and Graham 1978). Zinc deficiency is not widespread in the United States but can occur on weathered and coarse-textured soils and on calcareous soils and is accentuated by phosphate (Adams 1980). Iron deficiencies are very rare in the United States (Rhykerd and Overdahl 1972).

Molybdenum is essential for nodule function (Manns and Mosse 1980), and deficiencies are often corrected by liming (Rhykerd and Overdahl 1972). Cobalt is also required by rhizobia (Munns and Mosse 1980).

Research Needs

It is safe to assume that, on our productive soils, legume forage yields will continue to increase due to management and plant-breeding advances. This will put even more pressure on the soil scientist to provide a fertilizer program to meet plant needs. Advances in soil and plant analysis for predicting these needs will require continuous research input, and greater emphasis will likely be placed on the DRIS approach to facilitate interpretation of plant analyses. Of the nutrients, sulfur needs are probably the most consistently troublesome to predict; this requires research emphasis perhaps more at the ecosystem level so that S cycling can be predicted based on soil, plant, and environmental factors.

Much of the land in the United States is not suited to intensive crop production. Yet these lands are often being converted to row crops with adverse effects due to accelerated soil erosion. More research is needed to provide forage legumes adapted to these lands and to provide the soil fertility required for maximum economic production.

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Discussion

Marten: Is it possible that R. meliloti in Australia and New Zealand is more tolerant of low soil pH?

Roughley: It is possible, but I would expect the Australian strain to be common with a strain somewhere in the United States.

Marten: This may be a fruitful area for collaborative research, as we really can't answer this question.

Syers: Why is lucerne so responsive to potassium fertilization?

Keeney: Rate of supply from the soil is insufficient. In Wisconsin, cold soil temperatures also restrict potassium supply at some times of the year.

Helyar: Potassium fertilization of avocado affects disease incidence in that species; this applies differentially to the carrier forms of chloride and sulfate. Could this also apply to lucerne?

Keeney: That is a distinct possibility, but I am not familiar with this area of research.

Environmental and Management Limitations of Legume-Based Forage Systems in Australia

W.R. Stern[1]

Abstract

Most legume-based forage systems in temperate Australia are based on annual medics and subterranean clovers. In tropical and subtropical Australia, research is in progress on Stylosanthes, Centrosema, Desmodium and Macroptilium-based pastures, mostly perennial species.

Reasons are examined for the decline over the last 25 years in legume content of temperate pastures. A distinction is made between deterioration, i.e., the failure of legumes to regenerate, and ecological succession, i.e., invasion by non-legumes as a result of fertility improvement.

Edaphic factors such as soil pH, soil physical factors, nutrients and the rhizobium/legume symbiosis are discussed. Reference is made to major pests and diseases. Several agronomic factors are considered and their relation to management is discussed. The need for research on pests and diseases and on seed dynamics in different environments is emphasised.

To improve management practices, understanding is needed as to how production of forage legumes can be maintained and what contribution the legume makes to the nitrogen economy of the farming system. Properly designed computer models could aid in that understanding. Such simulations need to be considered in an economic context of farming enterprises.

Introduction

The purpose of this review is to consider ecological limitations and agronomic and management factors that influence the persistence and productivity of pasture legumes in ley farming systems in Australia. The original native pasture contained few legumes, was adapted to low fertility and poorly adapted to grazing. Almost all forage legumes in commercial use today were introduced. The areas in Australia where temperate and tropical legumes may be grown are depicted in figure 2 in "The Distribution and Use of Forage Legumes in Australia," by K.R. Helyar, earlier in this proceedings. In southern Australia, legume-based pastures have been developing for about 70 years, and annual subterranean clover and medics are well integrated into cereal/livestock enterprises (Poole 1983, Puckridge and French 1983). In northern Australia, investigations did not begin until the 1950's (Cameron 1977, Norman 1966, Winter et al. 1984), and ley farming systems are still developing (Wood and Fukai 1982, McCown et al. 1984); these are not necessarily based on annual species. The primary sources of information will be from work done in southern Australia and, where possible, this will be supplemented with information from northern Australia.

The Nature of the Problem

Why are forage legumes not used in certain areas? The economic circumstances of individual farmers will largely determine whether they sow forage legumes and whether they seek to pursue a ley farming strategy. Ultimately the question needs to be answered in terms of effects on animal and crop production and on incomes and their stability. This review addresses the question "what are the environmental and management limitations to legume-based forage systems?" Problems are likely to be site-specific, and consideration needs to be given to edaphic and ecological factors including nodulation, nutrient status, pests and diseases, and agronomic and management factors, taking into account relative costs of nitrogen either fixed by legumes or applied as fertilizer (see "Productivity and Economics of Legume-Based Versus Nitrogen-Fertilized Grass-Based Forage Systems in Australia" by R.J.K. Myers and E.F. Henzell, earlier in this proceedings).

It will be helpful to consider, first of all, some long-term issues arising from situations where legumes have been used for some time. The current pasture situation in southern Australia has been reviewed by Carter et al. (1982), by Reed and Cocks (1982), and in south western Australia by Ewing (1982). It appears the legume content of pasture is less now than 25 years ago and is disturbingly low. There is a need to distinguish between deterioration (i.e., failure of annual pastures to regenerate) and ecological succession (i.e., the invasion by non-leguminous species following improvement in soil fertility, particularly where the grazing has been heavy (Arnold et al. 1984, Gillespie 1983a)). Reasons for deterioration include loss of seed banks during the cropping phase or after heavy grazing, the narrowing of rotations so that ultimately legumes do not persist in a 1:1 system without re-seeding, a decline in soil structure, a reduction in fertilizer use, and increased soil acidity. Factors also mentioned were surface sealing and excessive run-off, inadequate burr burial in subterranean clover in the spring, and desiccation of seedlings due to false breaks at the beginning of the growing season. To this could be added the declining use of phosphate fertilizer on pastures because of rising costs.

In asking "What determines the success of subterranean clover strains in south western Australia?" Rossiter (1977) distinguished between "biological" and "agronomic" success. While agronomic success may be of more immediate concern, factors relating to biological success are important also. The earlier emphasis on seed-producing capacity (Rossiter 1966) has been tempered with emphasis now on a critical (or threshhold) seed-producing capacity; the relevance of this is depicted diagramatically in figure 1, after Rossiter (1977).

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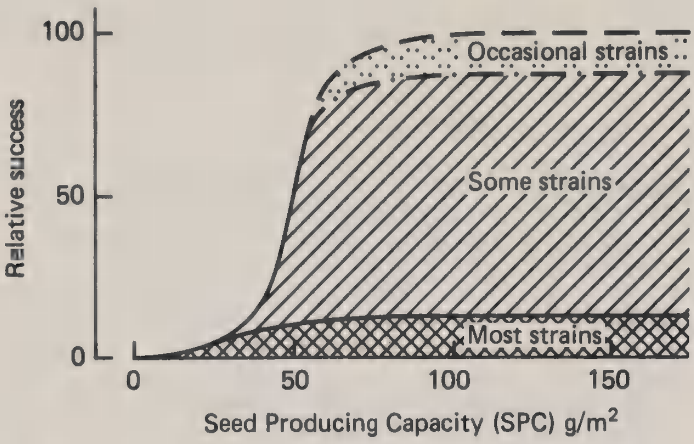

Figure 1--Schematic relationships between relative success and seed producing capacity in subterranean clover in mixed stands in a favourable rainfall environment. (After Rossiter 1977.) Success is determined by the annual dry matter production.

Edaphic and Ecological Factors

Provided a forage legume of the appropriate maturity is available and where growing seasons are short and rainfall is reliable, edaphic factors tend to assume greater significance than climatic ones. Soil pH, nutrition, and soil physical factors (compaction and aeration) all play a part in determining whether legumes can be maintained. The presence of appropriate strains of Rhizobia will influence the effectiveness of nodulation, and this is also an important factor in persistence.

Soil Factors

Soil pH influences the distribution of legumes (Robson 1969). Generally, soils in arid and semi-arid areas tend to be alkaline, but there are variations due to soil type. In temperate areas, some clovers are adapted to acid soils and grow well under low calcium conditions. Medics have a high calcium requirement and grow well on alkaline soils. However, because of the relation of the exchangeable hydrogen ion to other ions such as aluminium (Al), calcium (Ca) and other cations in soil colloids, the availability of certain mineral elements needs to be considered in relation to pH. This is particularly evident in the acidification that has been observed under continuously improved pasture (Porter et al. 1980, Bromfield et al. 1983).

There are not many studies that relate surface compaction of soil to physical properties (Graecen and Williams 1983) and fewer that relate it to the growth of and regeneration of pastures (see Barley and England 1970). Soil compaction by treading has been shown to reduce plant growth and persistence. Reductions in stolon length in clover in mixed stands of white clover/perennial ryegrass were observed by Curll and Wilkins (1983). This topic is worthy of further investigation (Carter et al. 1982). Seasonal soil water availability is also a factor in the regeneration and productivity of pastures (McCown 1973).

Intermittent and at times prolonged waterlogging during wet season is an important ecological factor in the performance of pasture legumes. There is a wide range of tolerance among species of legumes (Francis and Poole 1973, Whiteman et al. 1981) and within species (Francis and Devitt 1969, McIvor 1976).

Rhizobia

Bacterial strain specificity and nodulation characteristics in the host are heritable, and in order to exploit the potential of the rhizobium/legume symbiosis, the correct strain of Rhizobia should be used with the host species or cultivar (Gibson 1977, Date and Brockwell 1978, Date and Halliday 1980, Date 1983a).

Because of the paucity of indigenous rhizobia, together with inherent soil nutrient deficiencies, and because of the diversity of legumes in commercial use and problems of legume persistence, there has been a great deal of research on rhizobia in Australia (Vincent 1972, 1982). Between 1950 and 1975 there was an upsurge in the commercial use of inoculants, and there is now an effective network from research worker to farmer (Date 1969, 1983b; Brockwell 1982). Nevertheless, rhizobial survival in soil remains a problem in some areas (Parker et al. 1977), particularly in acid soils, and this can pose serious problems for legume persistence. See also the discussion by R.J. Roughley on competitiveness between organisms ("Nitrogen Fixation by the Legume-Rhizobium Symbiosis: The Role of the Bacteria") later in this proceedings.

Nutrient Status

For background, reference can be made to the several reviews of plant nutrient status in Australian soils (Stephens and Donald 1958, Williams and Colwell 1977, Williams and Raupach 1983). While Australian soils are inherently low in phosphorus (P), the application of phosphate fertilizer is now a standard practice in temperate Australian agriculture, so that P deficiencies have generally been remedied. However, because of the high cost of phosphate fertilizers in recent times, maintenance applications on pastures are being neglected, and phosphate deficiency in pastures is beginning to appear. This is an observation that has not been documented.

The majority of Australian soils show no serious problems of P fixation and substantial increases in the levels of plant-available P have resulted from the accumulation of residual P fertilizer. There have been some reports of losses of P by leaching from surface soils under pastures (Ozanne et al. 1961), but these are rare. Individual species differences in the use of phosphates have been reviewed by Andrew and Johansen (1978). It appears that species differ in their ability to take up and utilize P, and this was shown by Rossiter and Kirton (1956) for M. truncatula and T. subterraneum and for Desmodium unicinatum, Macroptilium lathyroides and Lotononous bainseii by Bryan and Andrew (1971). Such differences have been demonstrated between strains of subterranean clover (A.D. Robson and W.J. Collins, personal communication 1982) and Stylosanthes spp. (Jones 1974). In subterranean

clover these were due to differences in ability to take up P rather than in internal requirements; there was no evidence of differences in mycorrhizal development.

Potassium levels in Australian soils are generally adequate to maintain legumes, although, on specific soil types, exceptions can be cited (Rossiter 1947, Fitzpatrick and Dunne 1956, Paton 1956).

The need for sulfur (S) became evident when rock phosphate was being used in lieu of superphosphate during the 1939-1945 war and has become more pronounced as higher analysis phosphate fertilizers are being used more widely to save transport costs. Sulfur needs to be supplied regularly to maintain the legume content of pastures (McLachlan 1974). The residual effects of S are less marked than for P, due to greater leaching.

The extent of trace-element deficiencies in Australia was documented by Stephens and Donald (1958), and there are several reviews of the trace-element work in Australia (Loneragan 1970, Andrew and Kamprath 1978). The principal trace elements in short supply are zinc (Zn), copper (Cu), molybdenum (Mo), cobalt (Co) and to a lesser extent, manganese (Mn). Mo and Cu are required for effective nodulation. Where Zn is in short supply, additions can markedly improve the clover content of pastures; this does not apply to Cu to the same degree. Availability of Mo and Mn are dependent on the acidity of the soil and presence of other ions, particularly Al.

The question of when micro-nutrients need to be re-applied ought to be a priority area for research. To develop proper long-term fertilizer practices there is a need to establish internal and external nutrient requirements, particularly where legumes are grown in association with grasses (Kanehiro et al. 1983).

Fertilizer Practice

Basic knowledge about nutrients can be translated into fertilizer practice. The ideal situation is where soil and/or tissue testing can be used to manage the fertilizer regime year-by-year so as to maintain the legume component at a desirable level. "Strip testing," if properly laid out and carefully interpreted, can be useful in identifying fertilizer needs (Dear and Smith 1983).

Cox and Robson (1980) listed five factors for improving the efficiency of fertilizer use. These were soil and tissue testing to improve the basis for decision making, new fertilizers and improved methods of application, manipulating nutrients held in pools, the use of mycorrhizas, and selecting species and cultivars that are "nutrient efficient." To these could be added a knowledge of the competition between species for different nutrients, and this is discussed later.

Pests and Diseases

A spectrum of pests and diseases has been identified, and these may affect regeneration or productivity or both. While individually none has attained plague or epidemic proportions so far, they remain a "threat" in pasture production. The damage they may cause collectively has not been estimated properly, and, if economic losses were assessed, perhaps more research might be undertaken.

Accounts of pasture pests and diseases have been published (e.g., Moore 1970), and reports of sporadic outbreaks or accounts of life cycles can be found in the publications of departments of agriculture of each State (e.g., Barbetti et al. 1983).

In Southern Australia, the lucerne flea, red-legged earth mite, blue-green aphid (BGA), spotted alfalfa aphid (SAA) and Sitona weevil are the most serious pests of subterranean clover and medics. Red-legged earth mite and lucerne flea have been pests for much longer, and biological control has been attempted with moderate success (Wallace 1970). Screening for tolerance (Gillespie 1983b) is part of the National Subterranean Clover Improvement Programme in Australia. The major diseases of subterranean clover are clover-scorch (*Kabatiella caulivora*) (Chatel and Francis 1975, Helms 1975), rust, a variety of leaf spots, and clover stunt virus. Screening and selection work are in progress (Barbetti et al. 1983). Root rots are important in Victoria, New South Wales and Western Australia (Stovold 1974, Kellock et al. 1978, Barbetti 1984). It appears that appropriate fertilizer dressings may minimise the effects of root rots (MacKenzie et al. 1972). These diseases are sporadic in their attacks, and the ones more likely to affect persistence are clover stunt virus and seedling root rots.

In northern Australia, there is a wider range of pests and diseases. In *Stylosanthes*, stem-boring insects may attack some of the woodier species. However, anthracnose diseases (*Colletotrichum gleosporiodes*, *C. dematium f. truncata*) are much more serious, causing losses of dry matter and seed production (Burt et al. 1983). Although *Centrosema* has been attacked by root knot nematode (*Meliodogyne*) and legume little leaf virus in some experimental plots, neither appears to have become serious yet (Clements et al. 1983). Cercospora leaf spot and red spider can be a problem on foliage. In subtropical areas, *Desmodium* is attacked by the *Amnemus* weevil, which damages leaves; in more serious attacks the roots are damaged, even when sprayed with heptachlor or dieldrin. In tropical Australia, the weevil *Leptopius corrugatus* may cause damage (Imrie et al. 1983). *Uromyces appendiculatus* of Siratro is a new disease that could become significant.

Agronomic Factors

Seed Banks

Apart from some data by Carter and by Wolfe (Carter et al. 1982) and by Rossiter (1966, 1977, and personal communication 1984) and some data contained in articles by Biddiscombe et al. (1980), Gillespie et al. (1983) and Tothill and Jones (1977), there are surprisingly few data concerning seed banks in soil and the capacity for pastures to regenerate annually in a range of environments under commercial

farming conditions. There is a need for a systematic study of the natural dynamics of annual legumes in pastures along the lines described by Harper (1977), paying particular attention to recruitment and losses in pasture stands. Studies of the influence of physiological and environmental factors are also needed to interpret legume persistence or failure.

Competition

In considering the agronomy of legume-based forage systems, account needs to be taken of likely competitive factors. Understanding these is important in devising management strategies. In many parts of Australia, competition is largely between annual legume and annual legume, frequently of similar maturities and often under conditions of poor nutrient status.

Various studies of mixtures of strains (Burch and Andrews 1976, Collins et al. 1984) indicate that competition between strains does occur but also that "success in mixtures" may occur "without being superior competitively" (Rossiter and Palmer 1981). In a recent paper proposing a model to predict long term success in binary strain mixtures, Rossiter et al. (personal communication, 1984) combine life cycle parameters with crowding coefficient (de Wit's k) parameters (see Harper 1977) and amongst several conclusions state "Presently, there is a scarcity of relevant data on clovers. This is particularly so for the two parameters viz. de Wit k values and over-summer seed survival," further emphasising the need for studies of natural dynamics in existing pastures.

Another factor in competition may be for nutrients (Hall 1974, Snaydon and Baines 1981, Gilbert and Robson 1984). Because some species or some strains may be more efficient than others in the uptake of particular nutrients, this may determine the outcome of growing mixtures.

Rhodes (1981) has given a comprehensive review of the interplay of physiological factors in competition. He argues strongly for differentiating between yielding and competitive abilities and assessing both parameters in evaluating strains and in selecting components for mixtures. Rhodes and Stern (1978) and subsequently Rhodes and Mee (1980) presented data that showed that significant gains could be made by selecting legumes and grasses when testing them in stands with one another. This may be effective in environments where nutrients and moisture may be adequate and light is the major limiting factor; it may be less effective in other environments where intermittent moisture deficit or nutrient deficiency can limit growth.

Undersowing

In the ley farming system, competition arises when the forage legume is undersown with the last crop in the rotation, and this has given variable results. However, it is quite clear that there needs to be adequate seed production to achieve successful legume establishment in the first year of the ley (Poole and Gartrell 1970, Scott and Brownlee 1974, M.A. Ewing, personal private communication 1983). In a recent analysis, Rossiter et al. (personal communication 1984) suggest that unless hardseededness was high, clover may not regenerate to re-establish itself in rotations of one or two years of pasture.

Management Factors

Management is important in determining the persistence of legumes in pastures, and management decisions require an appreciation of the benefits to be derived from legumes, a sound understanding of the ley farming system, and a knowledge of costs. The following factors need to be considered: adequacy of soil nutrients; weather at the time of seeding; the likely success of establishment; cost of seeds, of seeding and of fertilizer; extent of weed, disease or pest problems; a knowledge of yield levels that provide an economic return; the intensity of grazing (Biddiscombe et al. 1980), and a knowledge of the nitrogen contribution by the legume to the farming system.

There is a tendency among Australian farmers to neglect pastures once they have been sown and also to manage stock rather than pastures. There may be sound economic reasons for such attitudes; one can only speculate on the causes. They may be due to the large between- and within-season variability in rainfall in many Australian environments, or they may be due to the options available to farmers operating within a cereal crop ley farming system. Whatever the reasons, in Australia, the accent in management of pastures appears to be on persistence rather than production. This contrasts with the situation in New Zealand, for example, where there is an emphasis on pasture management and differences between different management practices are measurable.

While the benefits from legumes have been recognised by farmers for a long time, data indicating what the benefits from legume-based pastures might be are fragmentary (Watson et al. 1977, White et al. 1978, Perry et al. 1980, Rowland et al. 1980, Poole 1983), and the topic warrants much more research. It lends itself to modelling (e.g., Russell 1981), but this has not been attempted widely.

The duration of the pasture phase in the ley farming system is determined by many interacting factors. Amongst them are the benefits that may accrue to subsequent cereal crops, the regenerative capacity of legumes and, most importantly, the relative profitability of the grazing and cropping enterprises (White et al. 1978). This too lends itself to modelling (Russell 1980) and has been researched inadequately.

In northern Australia, studies on the feasibility of legume ley farming are showing that while both animals and cereal crops benefit substantially from a ley, management to exclude grasses from the pasture is crucial (R.L. McCown, personal communication). Perry et al. (1980) have outlined advantages in favour of pastures without grasses, in southern Australia.

To reduce costs and accelerate the establishment of annual legume pastures after the cropping phase, undersowing with the last crop has been practised (Brownlee and Scott 1974). An important objective of the National Subterranean Clover and Improvement Programme (Stern et al. 1981) has been to develop subterranean clover lines with a high hard seed content to enhance clover survival after the cereal phase and to cope with unreliable breaks of season (Wolfe 1982, Puckridge and French 1983).

Conclusion

In this review, a wide range of information has been brought together in an attempt to answer the questions "what are the environmental and management limitations of legume-based forage systems?" Edaphic and climatic factors impose a large measure of site specificity, but if the nature of the problems is sufficiently well understood and defined, it becomes possible to adopt effective management strategies to maintain the legume component in pastures.

A great deal of understanding as a basis for management could be developed with properly designed computer models. These could be used to explore ideas and to evaluate strategies concerning:

1. The identification of specific characteristics of adapted forage legumes.
2. Methods of establishing forage legumes: e.g., undersowing vs. direct seeding.
3. Fertilizer practice with respect to:
   a. The contribution of nitrogen by legumes and its utilization by crops in the rotation.
   b. Maintaining and adequate phosphorous supply.
4. Maintenance of legumes in the face of competition from non-legumes as fertility rises.
5. Grazing management to make the best use of available feed.
6. Flock management to adjust grazing intensity to seasonal feed availability.

Considerably more research is needed on seed dynamics, on fertilizer practices, on pests and diseases of pastures and on pasture utilization by stock.

There is now sufficient information available and organisational systems are in place to screen and test genetically superior forage legumes for a wide range of specific environments. As practical scientists, we need to develop production packages with clearly demonstrated advantages.

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Discussion

Easton: Could you outline the difference in phosphorus utilization between subterranean clover strains?

Stern: This was in reference to unpublished work done by A. D. Robson and Collins at the University of Western Australia. The work was based on strains grown at different levels of P and internal and external P concentrations. The major findings were:

1. Difference between genotypes was marked at levels that were about two thirds of those P levels at which maximum yield was recorded.

2. There is variation in P response among genotypes. Older, more widely used cultivars were least responsive.

3. Differences among genotypes were due to ability to take up P, rather than to differences in internal requirements.

4. Rankings were similar, from field and glasshouse experiments.

5. The degree of the P-fixing capacity of soil could have an influence on the ranking of cultivars.

6. Mycorrhizal development was not associated with differences in genotype response.

Minson: Why do farmers manage their stock rather than their pastures?

Stern: I suspect the problem is economic rather than educational.

Lowther: Keith Helyar and Walter Stern have both mentioned the importance of mycorrhiza in Australian pastures. This area of research work has been much reduced in New Zealand because mycorrhiza do not appear to be significant in our pastures. What is the basis of this difference in emphasis?

Stern: The low nutrient status of many Australian soils may make mycorrhiza more important than in New Zealand. A recent review of the mycorrhiza work has been published. The reference is: Abbott, L.K. and Robson, D. 1982. The role of vesicular-arbuscular mycorrhizal fungi in agriculture and the selection of fungi for inoculation. Aust. J. Agric. Res. 33: 389-408.

Helyar: If mycorrhiza reduce the amount of phosphorus required by the plant, then development programs may be more economic.

Syers: Mycorrhiza fungi were deliberately left out of my paper. In New Zealand, mycorrhiza are unlikely to play a significant role in increasing the efficiency of use of soil and fertilizer phosphate, except on soils of very low phosphate status.

Environmental and Management Limitations of Legume-Based Forage Systems in New Zealand

G.W. Sheath and A.J. Harris[1]

Abstract

Numerous farm systems have been developed in New Zealand to provide a basic match between animal feed requirements and the wide range of pasture production levels encountered. Management options provide further flexibility in reducing the impact of variations in seasonal and annual pasture growth. Four farm systems are discussed to illustrate the interaction of management and production.

Management of in situ grazing requires strict stock control and adequate subdivision. Transfer of pasture to deficit or critical feeding periods through the use of long rotations is common to most systems, particularly during winter. Efficient use of peak spring pasture growth is achieved by the correct timing of lambing-calving and allocation of land to forage conservation. Maintenance of pasture quality in late spring-summer is critical to sustaining lactation and finishing stock. Integration of special-purpose species or supplements may improve feed supply patterns, but often it is uneconomic.

Introduction

Farm systems involving different stock types, stocking rates and production levels provide the major means of successfully exploiting the wide range of pasture production levels encountered in N.Z. farming. Within these systems, legumes provide herbage of high nutritive value for livestock; but, more importantly, they also promote herbage production from companion grasses through the development and maintenance of an improved nitrogen cycle. This association is the basis of achieving annual pasture production levels of 8-14 t DM/ha, and, in combination with in situ grazing, it provides low-cost pastoral systems.

Different farm systems attempt to match the demands of grazing animals with the general patterns of pasture production. Management options provide a further means of achieving improved concordance of feed requirements and pasture growth. Most importantly, management provides the flexibility to cope with variations in annual and seasonal pasture production. This ability to reduce the impact of environmental constraints is the basis of this paper. Four contrasting pasture production patterns (fig. 1) and associated management systems are considered to illustrate the limitations to which pastoral systems are exposed.

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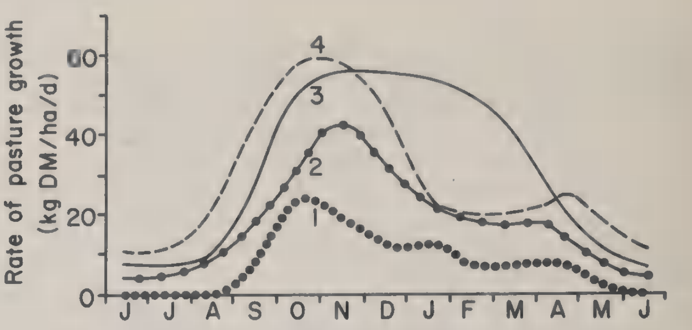

Figure 1--Generalized pasture growth for summer-dry South Island high country (1), summer-dry North Island hill country (2), summer-wet South Island finishing land (3), and summer-dry North Island dairying land (4).

South Island Hill and High Country Tussock Grasslands

This extensive farm type occupies approximately 4.8 million ha, or 37% of farmed grassland area in New Zealand. In general, it is located at higher altitudes (300-1,000 m) where winter temperatures are below the threshold for pasture growth for 3-5 months (Scott 1979). Fine wool sheep and store beef cattle are farmed on large holdings (1-10 thousand ha), which are stocked at 1-3 sheep equivalents per ha and produce 10-30 kg meat and 3-12 kg wool per ha.

Unimproved native tussock grassland communities principally consist of *Chionochloa*, *Festuca*, *Poa* and *Notodanthonia* spp. and may now include adventive grasses and weeds such as *Agrostis tenuis*, *Anthoxanthum odoratum* and *Hypochaeris radicata*. These grasslands are characterised by high biomass, slow organic matter breakdown, low levels and rates of nutrient cycling and a production pattern dominated by protracted, low winter growth rates (O'Connor 1966). Poor winter herbage production is the major constraint and has traditionally been overcome by low stocking rates and large holdings, winter forage crops, or emphasising non-breeding stock such as wethers.

Improvements in herbage availability, particularly for winter, are sought through the use of fertilisers and the introduction of clovers and grasses such as *Trifolium repens*, *T. hybridum*, *Lolium perenne* and *Dactylis glomerata* (O'Connor 1966). These developments may increase annual production from 2-3 t DM/ha to 5-10 t DM/ha. Adequate subdivision and the control of grazing animals is crucial to the efficient use of these improvements (O'Connor et al. 1982). Improved pastoral areas that are poorly fenced become preferred grazing zones. As a result, nutrient transfer occurs to outside areas and overall block utilisation declines (Abrahamson et al. 1982). Further, insufficient subdivision can restrict opportunities for forage conservation, which could improve nutrition at critical periods and the in situ transfer of autumn feed into winter. High financial costs of fertiliser and fencing limit this type of development at present.

An alternative development option involves the introduction of Lotus pedunculatus (Scott and Mills 1981). Being efficient in the use of available soil phosphorus and tolerant of acid soils high in exchangeable aluminium, this legume lends itself to a less costly development option. Its habit is well suited to extensive grazing management (Sheath 1981), but like T. repens it is frost-tender at high altitudes and unlikely to persist in areas drier than the sub-humid zone. For drought-prone areas, Medicago sativa is more suitable, but, because of establishment problems and more precise grazing requirements, it has yet to become more than a source of conserved forage to supplement grassland herbage (Musgrave 1983).

North Island Hill Country

This farm system occupies 3 million ha of hill land (25% of New Zealand's grassland) and traditionally carries breeding sheep and beef cattle with average annual production levels of 90-130 kg meat/ha and 30-50 kg wool/ha. These are obtained from low cost, permanent pastures based on phosphatic fertiliser, clover introduction, increased nitrogen availability and greater grass growth (Suckling 1975). Physical land variation (slope and aspect) and differences in seasonal and annual climate, pose major constraints in matching feed requirements with pasture supply where there is little practical or economic opportunity for conservation.

A wide range of pasture species exists in hill pastures, the most common being A. tenuis, A. odoratum, L. perenne, Lotus spp., T. dubium, T. subterraneum and T. repens (Rumball and Esler 1968). Fluctuations in the content of these species, and the development of distinct genotypes, provides some "inbuilt" flexibility to cope with variable moisture, fertility and grazing conditions (Macfarlane and Sheath 1984). Nevertheless, the constant pressures of environmental stresses maintain hill pastures in an unstable state that is unlikely ever to achieve a complete pastoral association of high-fertility demanding, erect and high-producing pasture plants.

Common to all hill country are the dominating effects of land slope and aspect on pasture production (Lambert et al. 1983). Temperatures and potential winter growth rates increase on steeper and more north-facing slopes, but these same physical factors accentuate summer moisture deficits through increased water runoff and evaporation (Radcliffe and Lefever 1981). In addition, slope and aspect induce preference-rejection of land and vegetation types by grazing animals and result in zones of over- and under-grazing and nutrient transfer (Gillingham 1983). Commonly, pasture on easier contours and warmer aspects is grazed in preference to that on steep and colder land.

Production and utilisation from the different land and vegetation types vary considerably, and ideally separate land classes require individual management. Division of paddocks into uniform aspects, slopes and vegetation types is the primary means of achieving management control (Suckling 1975). New developments for electric fencing and their acceptance in hill country has provided a rapid expansion of low-cost subdivision, but within-paddock variation will always remain. This can be partially countered by grazing pastures with high animal densities of 300-400 per ha for 2-4 days, as this reduces preferential grazing (Sheath 1983).

At stocking rates of 10-12 sheep equivalents/ha there is a continual need for flexible management, not only to buffer variations in pasture production but also to ensure the feeding of responsive stock at the correct time (Rattray 1981). Much of this flexibility is gained by manipulating lambing, calving, weaning and sale dates, thereby changing feeding requirements through differences in individual intake and animal numbers. Further flexibility is gained by the in situ transfer of pasture from non-critical to responsive periods or from surplus to deficit periods and then its subsequent rationing. A long rotation of 50-80 days' duration in winter achieves this transfer-rationing process and helps to reduce winter-early spring feed deficits. This management procedure combines well with the strategic use of low rates of fertiliser nitrogen during winter-early spring, and is also a means of maintaining a higher pasture mass with which to commence spring growth and post-lambing-calving nutrition (Smeaton and Rattray 1984).

Even with the inclusion of management adjustments in stock number and feed transfer, most hill systems are still unable to cope with the peak growth period of November-December. The development of surplus, rank pasture represents an immediate wastage of pasture quantity and quality (Sheath et al. 1984). At the extreme it creates a potential problem of pasture degeneration through the loss of productive legumes and grasses and reversion to scrub weeds. Integrated grazing of complementary animal classes is essential in minimizing this wastage. Within sheep-dominated systems, cattle are well suited for removing low quality roughage and maintaining pasture control (Suckling 1975).

While the transfer-rationing process of long rotations can help reduce the impact of summer deficit periods, the variable onset and duration of drought is difficult to counter fully. Maintenance of pasture density and quality and animal condition is important, but there appear to be no pasture management options at this time that fully substitute for water in providing sufficient quality herbage. Supplementation with silage or greenfeed crops is a possibility in some areas for ensuring that sufficient quality forage is available for the nutritionally important March-April ewe-mating period (Rattray 1983).

Intensive South Island Finishing Grasslands

These systems occupy 2.5 million ha of grassland and involve the intensive grazing of sheep and beef cattle on flat and undulating land for the purpose of finishing animals to prime condition. Climatic conditions range from the long, cold winters and cool, moist summers of Southland to the summer drought-prone areas of Canterbury. Lolium perenne predominates in pastures that may also include a wide range of sown (e.g., Phleum pratense/moist;

D. glomerata/dry) and volunteer grasses (A. tenuis, A. odoratum, Cynosurus cristatus, Poa spp.). Trifolium repens is always used, and, in areas subject to summer moisture stress, T. pratense and T. subterraneum are useful companions. Stocking rates are often 14-15 sheep equivalents per ha, producing 240 kg meat and 90 kg wool per ha.

In areas such as Southland, pasture production based on T. repens and L. perenne has a distinct winter trough and late spring-summer peak. Animal requirements are best matched to this pattern by using moderate stocking rates of ewes producing a high percentage of lambs (Harris and Hickey 1979). With little supplementation, rotational grazing management is required to minimize winter feed deficits. This involves the accumulation of pasture reserves before winter and subsequent rationing by a rotation of approximately 100 days (Cooney and Thompson 1979). While the development of substantial herbage mass by this management may promote tissue senescence, grazing pastures too frequently during winter reduces rationing power and may reduce spring pasture recovery (Harris and Brown 1971).

Winter management requirements also constrain mating and lambing dates. If mating is delayed to take advantage of better mid-spring pasture growth during lactation, insufficient pasture mass may accumulate during autumn for use in winter (Harris and Hickey 1979). Similarly, improved feeding of pasture to ewes at mating to increase fecundity conflicts with the need to create reserves of standing pasture for use when winter pasture growth rates are low. Supplementation (e.g., silage) at this time is the most reliable means of improving ewe ovulation rates, particularly where dry summer conditions may also be involved (Hayman and Munro 1983).

In addition to winter feed deficits, finishing systems in Canterbury have to contend with regular summer droughts. Variations in summer grazing management such as spelling, set stocking, fast or slow rotations, and topping or not topping have little effect on pasture performance (Vartha and Hoglund 1983). If dry conditions are prolonged or insect attack occurs, it is autumn overgrazing that has the greatest adverse effect on pasture survival and recovery in these summer-dry environments. These effects can be reduced by conserving surplus spring pasture, as hay or silage, for feeding in summer-autumn. Where possible, irrigation can remove many of the uncertainties from farming this land. Taylor (1974) described mean annual production from a non-irrigated Canterbury land pasture as 6,040 kg/ha ± 49%, while irrigated pasture at the same site was 11,870 ± 12%.

Lucerne (M. sativa) is an alternative forage to grass-clover associations in these drought-prone areas and of the 160,000 ha grown in New Zealand, 80% occur within finishing systems in Marlborough, Canterbury and Nelson. To achieve high production levels from lucerne, cool season growth should be transferred to early spring; commencement of spring grazing should be delayed for as long as possible; and ewes and lambs should be rotationally grazed before weaning (Janson 1974). In general, lucerne is superior to grass-clover pastures for finishing animals in warm-dry environments (Campbell 1967). Because of greater summer and poorer winter production, lucerne appears most suitable for finishing systems with a high summer feed requirement (Croy and Weeda 1974). Introduction of cool-season grasses into lucerne has improved the seasonality of production, but annual production has rarely been increased (Fraser 1983).

Provision of quality herbage is of prime importance in these finishing systems (Rattray 1981). However, this is often difficult to achieve during late spring-summer, when pastures may first be dominated by low quality stem growth and then experience dry conditions. Deterioration of pasture quality can be reduced by topping or silage conservation. Continuous, rather than rotational, grazing between September and December can also help maintain summer pasture quality by increasing white clover content (R.J.M. Hay personal communication). Red clover in grass-legume associations is another useful feed source for fattening weaned lambs, but red clover-dominant pastures should not be fed to ewes at mating because of phyto-oestrogenicity (Hay and Ryan 1983).

North Island Dairy Factory Supply

Approximately 90% of production achieved from the 2 million ha of dairy farming in New Zealand, is obtained from North Island factory-supply farms. This system occupies the more favourable climatic areas and fertile soils of N.Z. pastoral agriculture, but the narrow margin between pasture supply and demand means production is very sensitive to climatic vagaries and management errors. The traditional factory supply system of 2-4 cow equivalents/ha, 150-180 kg milk butterfat per cow, spring calving and 7-9 months of lactation, is principally structured to circumvent the greatest constraint to production, viz. seasonality in herbage production. High production per hectare in this system is achieved by using high stocking rates which maximise in situ grazing and minimise forage conservation (Bryant 1981).

Through diminishing cow condition at calving and cow nutrition during the first 2-3 months of lactation, winter feed deficits can reduce milk yields. The impact of winter deficits can be reduced by correctly timing the drying-off of cows in autumn, precise autumn-winter feed budgeting, and calving at the appropriate date (Bryant 1981). Cows in poor condition, resulting from delayed drying-off, require better winter nutrition if subsequent production is not to suffer. This extra nutrition will reduce post-calving feed reserves or require the provision of conserved feed that ultimately competes with mid-lactation nutrition. If drying-off is correctly timed and cow condition is satisfactory, then conservation needs are minimized and strict rationing of winter pasture by a long rotation of 80-100 days is sufficient to allow post-calving pasture reserves to accumulate (Bryant and Cook 1980).

In structuring winter rotations, a compromise between sufficient feed transfer and excessive herbage mass should be sought. Excessively long rotations that attempt to transfer autumn-grown feed

into early spring can ultimately reduce post-calving nutrition (Bryant and MacDonald 1983). Also, where winter-wet soils are prone to pugging damage, strict adherence to high animal density-long rotation grazing is undesirable in terms of pasture damage.

Pasture growth rates during early lactation can be increased with winter-early spring nitrogen applications, although continued use through spring can lead to depression of pasture and animal production and uneconomic returns (Bryant et al. 1982). Persistence of peak milk yields attained during early lactation depends on maintaining pasture quality and quantity during late spring-summer (Campbell and Bryant 1978). The balance between maintaining pasture quality and ensuring adequate summer feed is principally determined by allocating correct area ratios for grazing:conservation for the stocking rates involved. When pasture quality is low, production can be improved by cutting paddocks prior to grazing, or by topping after grazing (Bryant 1982).

Milk yields from February onwards are the most variable and reflect the impact of occasional summer droughts and feed deficits. While there are various short-term means of reducing these deficits, each has its own "inbuilt" cost. Silage supplementation requires extra conservation and reduced feeding efficiency, while irrigation responses are uneconomic in the long term (Holmes and McMillan 1982). The integration of herbage species such as Paspalum dilatatum, M. sativa and Zea mays, which are more productive and/or persistent than commonly used L. perenne and T. repens cultivars, has ultimately proven uneconomic due to reductions in cool-season herbage supply (Campbell 1982). Only where consistent and lengthy droughts are experienced on North Island central plateau pumice soils has widespread use of lucerne, and its associated requirements for conservation, been viable (Mace 1979).

Conclusion

Where environmental limitations increase seasonal and annual variations in pasture production, greater management inputs are required to achieve productive viability, particularly as farm systems intensify towards higher per unit area production (fig. 2). The ability of management to interact with environment and manipulate animal requirements and pasture availability is an essential ingredient in achieving high production from all N.Z. pastoral systems.

Research Requirements

More intensive use of grass-legume pastures in New Zealand would be aided by the following developments:

1. Identification of grass-legume associations which are more efficient in the productive use of available phosphate and nitrogen. This is essential to the maintenance and extension of complementary plant associations. Specifically, it is important to identify and develop more efficient forage legumes, compatible with intensive pastoral farming.

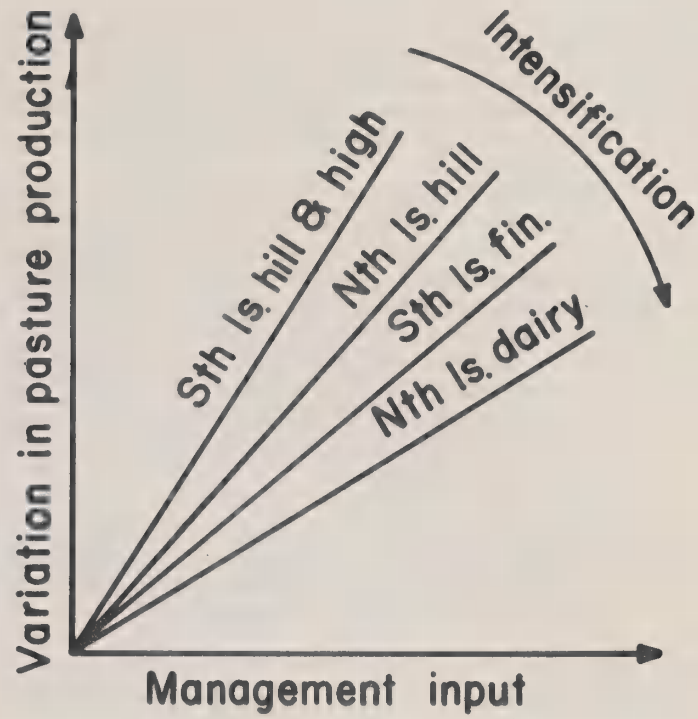

Figure 2--Relationship among variation in pasture production, farming intensification and the need for management input (farming systems as described for fig. 1).

2. Identification and integration into farming systems of forage plants which will reduce the impact of quantity and quality limitations imposed by soil moisture deficits. Persistence must be assured and cool-season production not jeopardised.

3. Improvement in the longevity of individual leaves of grasses such as ryegrass would help in reducing loss of leaf tissue, to the benefit of feed transfer in long rotations.

4. Further development of management systems incorporating a variety of pasture utilisation techniques to help meet the changing seasonal feed requirements of individual grazing animals at high concentrations.

5. Integration of current production and utilisation information into management-decision models, to aid the efficient manipulation of feed flow.

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Discussion

Clark: Do most farmers take any recognition of legumes in pasture management, or is management based on feed requirement only?

Sheath: It is dependent on intensity of farming. The greater quality of legumes is recognized on finishing properties where feeding of legume-dominant pastures to finishing stock is strategically sought. However, outside these areas little consideration is given to managing pastures specifically for their legume content.

Stern: Is rotational grazing practised during winter in New Zealand?

Sheath: Supplementary crops (e.g., swedes) for winter feeding are not very common now, and winter rotations (60-100 days) are the most common means of achieving stable nutrition on dairying, finishing, and most hill farms.

Burns to Minson: Is there a role for N.Z.-style intensification and rotational grazing in Australia?

Minson: There is less evidence for the advantages of rotational grazing in the drier Australian environment than in the moister N.Z. climate.

Sheath: The more extensive systems in New Zealand, like that found in our high country, are similar to extensive, low output systems in Australia and the United States. The large investment in intensification (e.g., fencing, etc.) of N.Z. lowland and hill country can only be justified if high output results.

Environmental and Management Limitations of Legume-Based Forage Systems in the Northern United States

Gordon C. Marten[1]

Abstract

The dominant forage legumes being grown in the Northern United States and in Canada are alfalfa (Medicago sativa L.), red clover (Trifolium pratense L.), and birdsfoot trefoil (Lotus corniculatus L.). Among the major climatic limitations to production of forage legumes in this region are constraints associated with light, temperature, moisture, and interactions among these variables. The most critical climatic problems are extremely cold and variable winter temperatures accompanied by uncertain amounts and distribution of insulating snow cover, lack of dependable moisture during the growing season, and excessively wet conditions in poorly drained areas. We need a better understanding of the physiological, morphological, and genetic mechanisms and interactions that affect forage legume production response and stand depletion in varying environments. Whereas seed production of alfalfa in the West has usually been sufficient to supply all of the northern United States, pollination, pest control, and technology problems remain. Red clover seed is usually adequately supplied as a byproduct of forage production. Lack of reliable supplies of birdsfoot trefoil seed requires research solutions. Vast information exists to ensure satisfactory conventional and minimum tillage establishment of forage legumes, but remaining problems include poor seedling vigor of some promising species and pest interference with seedlings. Pests (weeds, insects, nematodes, and diseases) of established legume stands represent a dynamic and ever-changing production constraint; this situation requires a research effort in integrated pest management and genetic selection that is never terminated.

Introduction

During the 14th International Grassland Congress in Kentucky, the newly prominent status of the legume in forage-livestock systems was evident throughout the world (Marten 1981). According to a tabulation of areas planted for seed certification (Association of Official Seed Certification Agencies 1983; table 1), the dominant forage legumes being seeded that are adapted to the Northern United States and Canada are alfalfa (Medicago sativa L.), red clover (Trifolium pratense L.), and birdsfoot trefoil (Lotus corniculatus L.). Of the other species adapted to northern areas, crownvetch (Coronilla varia L.),, sainfoin (Onobrychis viciifolia Scop.), and cicer milkvetch (Astragalus cicer L.) seed is also being grown for certification. Shipments of seed to retailers and farmers in the Northeastern United States (Pardee 1983) revealed an 11% increase in use of alfalfa, red clover, and birdsfoot trefoil in the past year accompanied by a 20% decrease in use of ladino clover (Trifolium repens L.) and alsike clover (Trifolium hybridum L.). In 1984, there were 65 cultivars of alfalfa, 7 cultivars of red clover, and 6 cultivars of birdsfoot trefoil available from seed distributors in Minnesota (Martin 1984).

Table 1 - Land area planted for certified seed production in the United States and Canada in 1983 (adapted from the Association of Official Seed Certifying Agencies Production Publication No. 37, 1983).

Species	Hectares
Alfalfa	53,970
Clover	11,006[1]
Birdsfoot trefoil	2,169
Crownvetch	631
Sainfoin	225
Cicer milkvetch	14

[1]Over half of this total (6,202 hectares) was red clover.

The subject "environmental and management limitations" implies the existence of nonlimitations or the optimal set of conditions. As Christian (1977) observed, "the notion of an optimal environment is open to criticism, since the requirements for maximum dry matter yield are not necessarily those which produce material of best quality or which promote highest seed yields or greatest persistence." He concluded (as I suggest we might) that, nevertheless, any study of growth (and I suggest adaptation) requires a comparison with a norm for a genotype under circumstances where development is not unreasonably restricted by any single external parameter. Indeed, because alfalfa is one of the best adapted, and often most productive, forage legumes in the Northern United States, we frequently compare the performance of all other alternative species to that of alfalfa. However, alfalfa seed production is difficult in the humid regions where it produces forage very well, and we cannot afford to manage it to ensure maximum persistence, because if we do (via infrequent harvest) we will end up with a low yield of a poor quality feed. With these concepts in mind, I will discuss some major factors that limit legume-based forage systems in the Northern United States. The soil environment is presented in "Edaphic Limitations and Soil Nutrient Requirements of Legume-Based Forage Systems," by Dennis Keeney, earlier in these proceedings, so I will not include it.

Climatic Limitations

Alfalfa originated in a climate characterized by hot, dry summers and cold winters, features typical of areas where it presently grows (Heichel 1982),

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including much of the Northern United States. This explains the large areas of alfalfa in the United States and why the majority of research concerning environmental and management limitations of legume-based systems has been done with alfalfa. In North America, alfalfa is most productive between 35° and 45° north latitude, but it also thrives in irrigated arid and semiarid regions (Heichel 1982). Lack of availability of a uniform supply of water in the humid region (41 to 61 cm rainfall) is often the major yield constraint, and extremely cold and variable winter temperatures, accompanied by variable insulating snow cover, can be a major survival constraint.

The clovers have a much wider distribution than alfalfa because of the large number of species, their generally wide adaptation to soil and climatic conditions, and their ability to reseed readily (Van Keuren and Hoveland 1984). However, the clovers are especially dependent on adequate soil moisture and a continual supply of rainfall. All of the better forage legumes are relatively intolerant of shade, and, with the exception of white clover, few of the cool-season legumes are morphologically as well adapted to grazing as are the grasses (Templeton 1976).

Lack of complete adaptation by the major species to light, temperature, and moisture variables helps explain why legume-based forage systems often require intensive management for success in the Northern United States.

Light

Photoperiod limits production and influences harvest management of forage legumes. Alfalfa, red clover, and birdsfoot trefoil are usually long-day species. Therefore, the length of growth periods between harvests that are commonly based on the onset of flowering may be partly determined by photoperiod (Heichel 1982). However, interactions between temperature and photoperiod complicate the timing of developmental stages. For example, increasing maximum daily temperatures from 15° to 27°C accelerated the onset of flowering of alfalfa, alsike clover, red clover, birdsfoot trefoil, and sweetclover when daylength was held constant (Marten 1970, Smith 1970). Most "double-cut" cultivars of red clover require at least 14 hours of light to induce flowering, but "single-cut" (mammoth) cultivars require 16 to 18 hours of light to flower (Taylor and Smith 1981). Birdsfoot trefoil also requires 16 to 18 hours of light for full flowering.

According to Christian (1977), low growth rates at short daylengths distinguish winter-dormant (hardy) cultivars of alfalfa from winter-active (nonhardy) cultivars. Hardy cultivars of alfalfa have a high percentage of plants with a long-day flowering requirement, whereas nonhardy cultivars have a high percentage of plants that are day-neutral (Massengale et al. 1971). Also, nonhardy cultivars have faster stem growth rates under specific mixtures of light wavelengths, especially at low temperatures (Christian 1977). Thus, the requirement for hardiness in our cold winter climate limits the yield capacity of alfalfa cultivars adapted to the Northern United States.

Whereas no evidence exists to suggest that changes in spectral composition during cloudy weather are large enough to alter plant growth, this possibility exists. Evidence does show that relative growth rates of alfalfa are increasingly reduced at light intensities below 50%-75% of full daylight. Also, as shoot length increases, shading of the lower leaves becomes an increasing limitation to alfalfa production because of leaf senescence.

Temperature

Growth rates of alfalfa are highest when daylight temperatures are in the region of 20°-25°C (Christian 1977). Thus, below optimum temperatures during the growing season are more often yield limiting than are above optimum temperatures in the Northern United States, although both situations frequently occur. Herbage yields of alfalfa, alsike clover, red clover, birdsfoot trefoil, and sweetclover increased as temperatures decreased from 27° to 15°C if yield was measured at a specific maturation stage (delayed maturity at cooler temperatures) rather than at a specific time interval (Marten 1970; Smith 1970). However, increasing maximum temperature from 27° to 32°C also delayed maturity of birdsfoot trefoil and increased its yield. Taylor and Smith (1981) reported that red clover produces best in areas that have moderate summer temperatures and that this species stores more carbohydrates when grown at 16°-24°C than at 27°-35°C.

Winterkilling, or lack of persistence associated with winter injury, is generally considered to be a greater temperature-induced limitation to production of forage legumes in the Northern United States than are unfavorable growing season temperatures. According to Jung and Larson (1972), alfalfa has survived temperatures as low as -64°C and as high as 49°C, and it grows naturally under more diverse conditions than most perennial species. Also, Reis (1982) reported that alfalfa used for dryland pasture or rangeland in the United States grows in areas having temperature ranges from as low as -46°C to as high as 49°C and that diurnal fluctuations of 40°C are common. However, temperature fluctuations that interfere with or undo the hardening process in autumn and winter are commonly considered to be a primary cause of stand loss. According to Smith (1981), cold hardening of alfalfa is favored by short daylengths (7 to 8 hours), generally lowering temperatures, an alteration of temperatures between warm during the day and cold at night, and adequate light intensity for good photosynthetic activity. These conditions usually occur naturally in the field during autumn. Whereas cooling temperature is of primary importance to the development of cold hardiness, any condition that stimulates production of top growth during autumn can retard hardening. Hardy cultivars have a progressively slower rate of regrowth after harvest and a more decumbent growth habit (rosette-type) than do nonhardy cultivars with the onset of the short days and cool temperatures of autumn.

Thus, we have the dichotomy of desiring on the one hand an alfalfa plant that regrows rapidly to provide high yields during the growing season and on the other hand one that has slow regrowth in autumn to ensure its winter hardiness. We are forced to

consider both properties simultaneously, and we settle for the intermediate regrowth characteristic.

Other temperature-induced causes of winterkilling of legumes include formation of ice sheets after rains or snow thaws (smothering of plants due to lack of oxygen) and desiccation and/or mechanical damage caused by heaving of crowns and roots out of the soil (due to alternate freezing and thawing in the absence of insulation provided by snow cover).

Moisture

Water Deficit. According to Heichel (1982), "alfalfa has acquired the reputation of being an extravagant consumer of water, despite considerable evidence that this is an unbalanced verdict." In fact, experiments in various regions have shown that alfalfa consumes similar amounts of water to that of other "full-cover" crops. Water use is more dependent on length of the growing season, proportion of ground cover, rooting depth, and crop yield than it is on plant species.

Obviously, seedbed moisture must be adequate for germination and optimum seedling emergence of all forage legumes. Also, Perry and Larson (1974) reported that stem number per plant, number of internodes per stem, and individual internode length of the primary stem of four cultivars of alfalfa were greatly reduced by water deficits (49% of field capacity). Two cold-hardy cultivars produced more internodes per stem than did two nonhardy cultivars when soil moisture levels were either adequate (100% of field capacity) or deficient. However, reduction of internode length due to moisture stress of nonhardy cultivars exceeded that of hardy cultivars, which indicated that hardiness characteristics may be useful in predicting cultivar response to moisture stress.

Lorenz (1982) suggested that introduction of alfalfa to arid and semiarid grasslands is a means of increasing animal output from a smaller grazing hectarage with a minimum of fossil fuel energy input. In glasshouse or field studies on the High Plains of Wyoming, Fairbourn (1982) found that alfalfa, alsike clover, sainfoin, and cicer milkvetch did not differ significantly in water-use efficiency, but cicer milkvetch had a low transpiration rate compared to the other species. White clover is a very shallow-rooted species, which makes it particularly susceptible to dry soil conditions. Thus, its contribution to pastures of the Northern United States (where it has either been seeded or naturally occurs) is much greater in wet seasons.

Generally, low soil moisture levels favor hardening and cold tolerance of alfalfa (Paquin and Mehuys 1980). However, they found that drought and low temperature stresses had additive influences on plant survival following freezing. Stout (1980) discovered that water stress during periods of both cold acclimating (2°-9°C) and nonacclimating (18°-20°C) temperatures increased the cold hardiness of alfalfa plants that were later frozen at -3.5°C.

Generally, Heichel (1982) concluded that, if water uptake were the only consideration, plant growth would be greatest when the soil was at field capacity (100% water availability).

Irrigation. Heichel (1982) reviewed principles that govern the water needs of alfalfa grown under irrigation, including critical water-demand periods, water requirements of growth, and consumptive water use. He also reviewed numerous irrigation trials which documented that water supply is often a major deterrent to alfalfa productivity when precipitation is deficient during critical growth stages. He cited results that suggest that rate of irrigation may be more important than timing, and, because rooting depth is often governed by water infiltration depth, the range of optimal water supply may be quite narrow. Water management is crucial for alfalfa production, because underirrigation causes a reduced yield, whereas overirrigation causes stand losses (Donovan and Meek 1983).

Carter and Sheaffer (1983) found that irrigation could be used efficiently for alfalfa production on coarse-textured soils in Minnesota by moderate water applications at 50% depletion of extractable soil water, an apparent threshold for maintenance of favorable plant water status. Benz et al. (1982) discovered that water table depth affected yield of irrigated alfalfa on sandy soils in Canada's Northern Great Plains; the optimum water table depth for maximum yield was between 1 and 2 m.

Because of sporadic rainfall distribution leading to water-deficit periods rather than continuous stress, and usually adequate seasonal rainfall for economic production, irrigation of forage legumes is not commonly recommended in the humid regions of the United States.

Water Excess. Alfalfa is highly susceptible to waterlogging, although cultivars differ in their tolerance. According to Heichel (1982), the initial effects (root xylem necrosis and yellowing and wilting of leaves) are usually attributed to lack of oxygen in the root zone, which causes formation of toxic substances. As Dennis Keeney has pointed out in "Edaphic Limitations and Soil Nutrient Requirements of Legume-Based Forage Systems," earlier in these proceedings, the low soil pH associated with poor soil drainage can induce aluminum (Al) and manganese (Mn) toxicity.

Whereas the primary symptoms of waterlogging may not be caused by pathogens, wet soils also enable *Phytophthora* oospores to germinate and release zoospores that infect alfalfa roots. According to Frosheiser and Barnes (1973), *Medicago sativa*, *M. falcata*, and *M. lupulina* are susceptible to *Phytophthora megasperma* in the field. However, Thompson and Fick (1981) found that in most cases, the negative response by alfalfa to flooding (ceased root growth and 50% reduction in top growth within 2 to 8 days) occurred before *P. megasperma* had an influence. This argued for a physiological rather than pathological basis for the injury. Barta (1980) concluded that waterlogging injury of alfalfa and the accumulation of ethanol under root anoxia may be causal agents which facilitate or promote infection by *P. megasperma* zoospores and lead to "root rot." Also, Suzuki (1981) reported an accumulation of ethanol and methanol, a

solubilization of proteins, and a decrease in soluble carbohydrates in waterlogged alfalfa roots during simulated midwinter thaw. He concluded that two physiological traits associated with alfalfa survival of a midwinter thaw (following hardening) appeared to be the plant's ability to maintain freezing resistance during the thawing period and its ability to remove ethanol quickly after waterlogging.

Heinrichs (1970) reported the following flooding tolerance of nine legumes:

Species	Days flooding tolerant
Birdsfoot trefoil, white clover, and strawberry clover; (Trifolium fragiferum L.)	20
Red clover, alsike clover, and alfalfa ('Rambler')	15
Sweetclover (Melilotus alba Desr.) and cicer milkvetch	10
Sainfoin	5

He concluded from a glasshouse experiment that plants persisted if flooding was not prolonged beyond the indicated time and that yellowing of leaves was an excellent indicator of flooding damage. These differences in flooding tolerance help explain why Wahab and Chamblee (1972) found that in contrast to stand losses of alfalfa and crownvetch due to repeated irrigation, yields of ladino clover increased by 19%. The irrigated alfalfa and crownvetch also had severe disease infestations.

The tolerance of birdsfoot trefoil to flooding and to poorly drained soils may be explained by research conducted by Barta (1980). He found that after 7 days of flooding, alfalfa had much more severe shoot injury, reduced root carbohydrates, and reduced rates of acetylene reduction compared to those of birdsfoot trefoil. Whereas induction of alcohol dehydrogenase (ADH) activity was very rapid, and ADH reached similar levels in both species, ethanol concentration in birdsfoot trefoil roots was several-fold lower. This indicated that birdsfoot trefoil may effectively remove ethanol from its flooded roots.

Jung (1975) pointed out that another cause of legume stand loss on wet soils is increased winter heaving (caused by freezing and thawing) in expandable silty soils that have no snow cover.

Legume Growth Models

A number of simulation models of forage crop growth have considered climatic and other limitations of legume-based forage systems for ruminant production (Holt et al. 1975; Bula et al. 1975a, 1975b; Miles and Peart 1975; Fick 1975, 1977; Holt et al. 1981; Smith and Loewer 1981; Smith et al. 1981). The latter two are subroutines that generate crop growth information constructed as independent models within the large scale Kentucky BEEF model which assesses the consequences of a change in single components of a complex system for beef cattle production. When Fick (1984) regressed field observations on eight simple dynamic simulation models of alfalfa production, he found that the best model included factors for production potential, heat summation, soil water holding capacity, and cutting management. These growth models are useful to researchers as they deliberate knowledge deficiencies as well as to farm advisers and cattle producers.

Seed Production and Supply Limitations

Some of the limitations to production of high-quality alfalfa seed can be determined from Marble's (1982) list of requirements for production: adequate pollination; proper control of harmful insects; proper irrigation; adequate row spacing, plant population, weed control, and harvest practices; cultivars that have high-seed-yield characteristics; and a rain-free climate during seed maturation and harvest. The introduction of the alfalfa leafcutting bee (Megachile rotundata (Fabricus) as a pollinator has revived the alfalfa seed industry in Canada (Goplen et al. 1980); several other bee species, including honey, bumble, and alkali bees have been used as alfalfa pollinators throughout the world, but with little success in Canada.

Rincker et al. (in preparation) pointed out that alfalfa seed production is best in areas where clear, sunny, warm summer days with little or no rain prevail. These climatic conditions promote flowering and long periods for pollination by bees. They stated that skillful application of irrigation water to establish a desirable moisture stress during alfalfa plant flowering is one of the most critical factors for successful seed production. Although alfalfa seed is produced in at least 20 states in the United States, about 75% of the crop is produced under irrigation on less than 75,000 hectares in five of the Western States (Rincker et al., in preparation). Also, 97% of the Canadian crop is produced in three of the Western Provinces.

Kalton and Brown (1981) summarized alfalfa seed production statistics and yields per hectare for the major producing States and for the United States over a 40-year period. They concluded from a survey questionnaire sent to more than 40 alfalfa seed experts that: (1) we have ample conditioning capacity, suitable hectarage, experienced growers, and qualified managers and fieldmen in many areas of the West; (2) production has usually been sufficient to satisfy demand in spite of production declines in recent years; (3) recently, production problems and sometimes reduced yields per hectare have threatened the economic stability of the alfalfa seed industry in several U.S. areas, indicating the need for more research. Among these production problems were pollination, insect and disease control, and out-of-date technologies.

According to Taylor and Smith (1981), seed production of red clover has traditionally been secondary to forage production and a by-product of hay or pasture; common seed of unknown cultivar

parentage is still sometimes being produced. As with alfalfa, red clover seed production is superior in the Northwestern States because of availability of controlled irrigation and lower humidity. However, about 50% to 55% of the red clover seed crop is produced in the humid Midwest as a secondary crop to forage production (Rincker and Rampton 1984). Seed of other true clovers and the remaining red clover is produced principally in the irrigated areas of the arid Western States. Declines of white clover seed productivity in Idaho could be partly traced to severe virus infestations, especially in the third production year; a new cultivar, 'Star', had superior seed yields (Ensign 1981). A small amount of white clover seed is harvested from pastures in the Southeastern States. Production of alsike clover seed has "seemingly ceased since the 1950's"; our domestic supply is now imported from Canada (Rincker and Rampton 1984).

A major restriction to birdsfoot trefoil use has been the lack of reliable seed supplies of improved cultivars (McGraw and Elling 1982). McGraw and Beuselinck (1983) listed two major factors that are responsible for low seed production by birdsfoot trefoil: (1) low partitioning of assimilates to seed yield and (2) an indeterminate flowering habit accompanied by dehiscent pods that shatter before harvest can be accomplished. Other factors include preferential pollination by honey bees of other nearby crops (such as sweetclover) and harmful insects which cause bud blast or totally inhibit flowering. Because birdsfoot trefoil pods dehisce excessively when the relative humidity of the atmosphere falls below about 50%, much of the seed is produced in humid areas, including such States as Minnesota, Wisconsin, and Michigan (the upper peninsula).

Limitations in Establishment of New Stands

Conventional Establishment

General Limitations. Many legumes contain a large percentage of hard seeds which are impermeable to water and, therefore, not capable of imbibition until the seed coat is scarified. Cooper (1977) reviewed reports showing a mean of 64% hard seed in alfalfa and of more than 75% in crownvetch and cicer milkvetch. Hand-harvested birdsfoot trefoil seed may be 90% hard, compared to only 40% hard following harvest by a combine (Grant and Marten 1985). Cooper (1977) listed depth of seeding (for most forage legumes seeding depth should not exceed 1.3 cm) and seed size (large seeds with large cotyledonary areas needed for fast initial growth) as potential establishment limitations.

Recommended seeding rates for forage legumes have not been standardized in the United States, probably because conditions of seedbeds vary greatly. According to Sund and Barrington (1976), if 80% of the alfalfa seed planted were to produce plants, about 3 kg/ha would be more than adequate to produce an excellent stand. But, because only 20% to 40% establishment is usual with most conventional farm seeding machines (assuming completely tilled seedbeds), and because an ideal seedbed cannot always be prepared, a seeding rate of about 6 to 12 kg/ha may be required. Seeding in excess of about 12 kg/ha is not usually economical because seed costs above this rate are not recovered by increased forage yields, even during the seeding year. Sheaffer and Swanson (1982) concluded that even for sod-seeding (minimum tillage), increases in alfalfa and red clover seeding rates beyond those usually recommended for conventional seedbeds were beneficial only when competition from unsuppressed grasses was great.

Poor seedling vigor of some legumes, such as cicer milkvetch and crownvetch, is a well-documented establishment limitation. Townsend (1980) bred 'Monarch' cicer milkvetch specifically to improve seedling emergence. The northern-adapted clovers are relatively easily established because of their rapid seedling emergence and good seedling vigor.

Weed Control. Weed control in conventional establishment of forage legumes has received vast attention in the United States. Schreiber (1976) contended that high weed densities during alfalfa establishment in wet years caused less yield loss than low weed densities in dry years. Also, in most cases, first year competitive effects from weeds are not measurable in subsequent years, although moisture availability can influence the response. Duke (1975) agreed that many studies showed that controlling weeds in a seeding will increase alfalfa plant density the first year, but density differences are not usually evident by the following year. Schreiber (1976) concluded that the most efficient and effective method for weed control in establishing alfalfa is the use of preemergence herbicides followed by early postemergence herbicides if needed.

According to Peters and Peters (1972), in addition to competition for water, nutrients, and light, some weeds may reduce alfalfa yield through the production of toxins or growth-inhibiting materials. However, very little sound evidence exists to substantiate the extent of this problem. Currently, there is also disagreement in the United States as to whether alfalfa is self-inhibiting (allelopathic) when new stands are seeded in areas where alfalfa was recently grown. Cultural practices, such as using clean seed, fallowing, selecting planting dates, clipping weeds, and using companion crops continue to be valuable alternatives in reducing weed competition when establishing alfalfa, but herbicides are being increasingly used for this end. The major failings of herbicides are: (1) they sometimes injure alfalfa, (2) individual herbicides do not control a sufficiently wide range of weed species, and (3) weed grasses cannot be removed from alfalfa-forage grass mixtures.

The use of a companion crop with new seedings of legumes (such as a small grain crop, flax, or canning peas) is essentially the substitution of a more desirable and/or less competitive plant population for another (weeds). Early removal of companion crops enhances the chances for successful establishment of the legume.

If one has the right kind of weeds (those having high forage quality), adequate moisture, and not so dense a stand that light is greatly excluded from

the legume seedlings, the most energy-efficient approach may be to not use herbicides but instead to use the mixture of seeded legume and volunteer weeds for forage. Whereas this approach involves an element of risk based on producer judgment, risk management is an integral part of energy-efficient agriculture.

Minimum Tillage Establishment

Light and moisture are often the most limiting factors during establishment of forage legumes in existing grass sods. Nevertheless, Wolf and White (1984) argued for use of minimum tillage (or "sod-seeding") because of the threat of soil erosion while new seedlings are becoming established in conventional, well-tilled seedbeds. In addition to conserving soil, time, and machine fuel, minimum-till or no-till seedings may actually conserve moisture that is already present in the seedbed and reduce water run-off in rolling terrain. They listed five imperatives to successful establishment of alfalfa via minimum tillage methods: (1) living competition must be controlled; (2) heavy thatch and plant growth tall enough to shade the soil surface must be removed; (3) the seedling must be protected against a wide spectrum of insects via use of an insecticide; (4) seed must be placed in the soil, but no deeper than about 2 cm; and (5) soil fertility must be medium to high with a pH of 6.4 to 6.7. In addition, management after seedling emergence must favor the weaker species if a mixture is to be maintained (Evans 1980). He suggested that close grazing prior to and after seeding as well as either tillage, herbicide, or a combination of the two should be used to reduce the competitive advantage of the established grass. However, according to Martin et al. (1983), grass suppression with herbicides may not insure successful alfalfa establishment via minimum tillage under low rainfall conditions.

Numerous researchers agree that red clover and white clover are most easily established of the common northern-grown forage legumes via minimum tillage. Birdsfoot trefoil, crownvetch, and cicer milkvetch are not as easily established via minimum tillage as alfalfa or the clovers because the former lack seedling vigor. In Minnesota studies with alfalfa, red clover, and birdsfoot trefoil interseeded into permanent grass sods, application of 30 to 60 kg N/ha before seeding often enhanced early legume seedling growth when soil N was deficient (West et al. 1980).

George (1984) successfully established alfalfa, red clover, birdsfoot trefoil, and sweetclover in Iowa by "frost seeding" in late winter (March) into undisturbed swards of three depleted cool-season perennial grasses. However, frost seedings of crownvetch, white clover, alsike clover, and cicer milkvetch were not successful. We have also succeeded with frost seeding of red clover into vigorous stands of cool-season perennial grasses in Minnesota. The freezing and thawing action of the soil in late winter allows the legume seeds to become established without tillage.

Slugs (Derogerus spp.) and nematodes have recently been shown to seriously damage legume seedlings that have been planted in minimum tillage pasture renovation programs in the Northeastern United States and in the Maritime Provinces of Canada (Sheaffer et al. 1982).

Pest Limitations in Established Stands

Weeds

Studies in established stands of alfalfa show that weed removal sometimes aids alfalfa production but often reduces total phytomass yield (Duke 1975). Sheaffer and Wyse (1982) concluded that because control of dandelion (Taraxacum officinale Weber) in established alfalfa did not increase total forage or alfalfa yields or increase forage quality in a Minnesota experiment, they could not recommend herbicide applications for dandelion control. According to Duke (1975), no studies had yet answered the question, "Did weeds cause the alfalfa stand to become thin or did the stand become thin and the weeds encroach?" Most investigators endorse the latter explanation, which accounts for the failure of weed control in many pure legume stands to cause yield increases and sometimes instead to cause total yield decreases.

However, when the encroaching weeds are toxic, of poor forage quality, or likely to become a menace to crop production generally in an area, prudent producers attempt to control them. Indeed, if we consider a "weed" as "a plant out-of-place or unwanted," then we might consider an overabundance of forage grasses in mixture with a desired legume to be in the weed category. Triplett et al. (1977) evaluated several herbicides for the "management of species composition" in established alfalfa swards which had become colonized by forage grasses as well as dandelion. The found that a grass herbicide reduced Kentucky bluegrass (Poa pratensis L.) and increased the alfalfa component as well as alfalfa yield without reducing total forage yield in Ohio. Heinrichs et al. (1982), also in Ohio, found that a grass herbicide sprayed in late autumn was beneficial to maintaining ladino clover in mixture with Dactylis glomerata L. if the herbicide was applied 1 year during a 3-year period.

Recently, several new herbicides have proven useful as grass killers when applied postemergence to seedling alfalfa, birdsfoot trefoil, sainfoin, cicer milkvetch, red clover, and other forage legumes without injury to the legumes. These herbicides will undoubtedly also become valuable as a means of keeping grasses from invading pure stands of mature legumes, and U.S. scientists are awaiting clearance labels to allow their use (Jordan 1983). However, Jordan concluded that the best weed control program in alfalfa is good management and control of insects and diseases that will ensure a strong, healthy stand.

Van Keuren (1980) reported that the new rope-wick or roller applicators offer selective control of tall-growing weeds in cases where broadcast spraying of herbicides would seriously injure the legumes. He also suggested that grazing animals, particularly sheep, will utilize many weeds and we should allow them to help keep weeds under control because mowing is too expensive. In fact, Marten et al. (1983) and Marten and Andersen (1975) found that some perennial and annual weeds that commonly invade alfalfa in Minnesota have excellent nutritive value and acceptable palatability to grazing sheep. We

concluded that the intrinsic forage quality significance of common nontoxic weeds must be decided for each individual species and situation rather than generally.

Diseases and Nematodes

Sheaffer and Barnes (1984) concluded that forage legumes are generally quite susceptible to crown and root rots as well as nematodes that impede persistence and to foliar diseases that reduce yield and forage quality. The clovers are also especially susceptible to viruses. Leath and Hill (1975) agreed that the root and crown rot complex is a major limiting factor in legume stand persistence. They pointed out that viruses, foliar diseases, and nematodes reduce plant vigor and undoubtedly reduce the ability of plants to withstand root and crown rots. Also, the latter probably make plants more susceptible to stress injury.

Graham et al. (1979) listed more than 10 bacterial diseases, more than 26 fungal diseases, 5 virus and mycoplasmalike agents, and more than 18 nematodal diseases that attack alfalfa. Of these, the Certified Alfalfa Seed Council (1981) in the United States listed 16 major diseases of alfalfa that occur in northern areas.

Plant breeders have controlled some serious alfalfa diseases such as bacterial wilt, anthracnose, and phytophthora root rot via release of resistant cultivars. Rhodes (1983) listed six other options for disease control in alfalfa and other legumes: (1) correct site selection, (2) improved soil drainage, (3) alteration of fertilizer regimes, (4) adjusted cutting schedules, (5) crop rotation, and (6) chemical control. Rhodes suggested that chemical control can be efficacious, economically justifiable, and in some cases, extremely profitable. Although no chemicals are registered for use as foliar sprays for control of alfalfa diseases in the Eastern United States, fungicidal compounds may be more widely used as new data become available. For example, Gilchrist et al. (1981), in California, showed that fungicidal control of crown rot fungi with chlorothalonil resulted in 20% to 25% annual yield increases in nondormant alfalfa. Also, Sheaffer et al. (1982) reported in Minnesota that a combination of a nematicide and fungicide could control a nematode-fungus disease complex likely responsible for poor alfalfa seedling establishment and poor yields on a sandy soil.

Taylor and Smith (1978) reviewed two decades of progress made by red clover breeders in development of resistance to seven specific diseases, nematodes, and the devastating root-rot complex. They pointed out that root-rot organisms decrease persistence, especially when clover is grown in the same fields for many years, when cultivars are introduced from exotic regions, and when physiological hazards are increased. They concluded that breeding for resistance to the root rot complex may be expected to be effective only by development of broad resistance to a wide variety of organisms.

Root and crown rot complexes are also often considered to be the most important diseases of birdsfoot trefoil, white clover, sainfoin and other forage legumes adapted to the Northern United States. For example, Auld et al. (1977) reported that root and crown rots greatly impeded persistence and forage yield of sainfoin in Montana and that none of 11 species of Onobrychis was immune to these rots.

Insects

Numerous insect species damage forage legumes, but insects are usually more species specific than are legume diseases (Sheaffer and Barnes 1984). The Certified Alfalfa Seed Council (1981) listed 13 insect pests that cause damage to alfalfa in the Northern United States. According to Willson (1983), the alfalfa insect pest complex changes annually. The potato leafhopper [Empoasca fabae (Harris)], a yearly migrant from the South, has been and remains the major alfalfa insect pest throughout most of the Northern United States.

Insects such as potato leafhopper, meadow spittlebug [Philaenus spumarius (L.)], alfalfa weevil [Hypera postica (Gyllenhal)], and pea aphid [Acyrthosiphon posum (Harris)] may cause reduced forage quality as well as reduced yields of alfalfa (Barnes and Gordon 1972; Cuperus et al. 1982, 1983). Insecticide sprays were the only known control method for potato leafhopper (Byers and Hower 1976). Some degree of cultivar resistance has been accomplished by plant breeders against some alfalfa insects such as alfalfa weevil, but insecticides are often relied upon for control of this and many other insect pests. Also, management practices, such as early cutting, are frequently used to guard against insect attack. Hendrickson (1976) also suggested that biological control of the alfalfa blotch leafminer [Agromyza frontella (Rondani)] which was first observed in the United States in 1968, appeared possible if European pupal parasites could be established. Recent research in Kansas (Certified Alfalfa Seed Council 1984) by Sorensen also indicates that sticky-haired alfalfa may have a biological defense against alfalfa weevil and potato leafhopper.

Taylor and Smith (1978) reviewed published reports of the existence of natural or plant-breeder-induced resistance by red clover to nine insect pests. They reported that red clover resistance to the potato leafhopper probably resulted from natural selection for pubescence. According to Taylor (personal communication 1984), the decline of red clover stands in areas of adaptation in Central and Northern United States can often be attributed to rapid deterioration of the taproot caused by root rots as well as injury from insects such as the clover root curculio [Sitona hispidula (F.)].

Alfalfa insect control via use of predictive models has been proposed in several northern states (Fick et al. 1976; Ruesink 1976; Shoemaker 1976). These simulations of crop-insect interactions could potentially determine the most economical management strategy for insect control. Fick et al. (1976) stated that if their model was correct, early harvesting would be effective in controlling alfalfa weevils, and insecticides would usually be needed only at combinations of low parasite populations and above average weevil numbers.

Harvest Management Limitations

The proper cutting or grazing management for forage legumes usually represents a mediation between frequent harvest to achieve the feeding quality needed for high animal performance and infrequent harvest to ensure maximum phytomass yield and maximum persistence in northern U.S. climates. In the latitudes between about 39° and 45° north, three to four growth cycles of alfalfa that each mature up to early flower stage may be harvested for conserved forage or pasture while maintaining an adequate to excellent stand (Smith et al. 1968). In this region, other leading legumes, such as red clover and birdsfoot trefoil, should typically be allowed longer growth periods (to reach greater flowering) to enable their long-term persistence (Smith 1965, Sheaffer et al. 1984).

According to Smith (1981), as leaf-area-index increases and as photosynthesis exceeds respiration in the field, total nonstructural carbohydrates (TNC) are stored in the basal tissues of legume plants, especially alfalfa roots. Then, after defoliation (when respiration again exceeds photosynthesis), energy for regrowth is derived from the stored TNC. However, Chatterton et al. (1974) and others have contended that although there is an association between regrowth initiation and root TNC storage, causal relationships have not been absolutely proven. We also know that legumes which display rapid regrowth in summer (such as alfalfa) can generally be completely defoliated more frequently than can those that regrow more slowly (such as birdsfoot trefoil or the clovers). Then too, Chatterton et al. (1974) found that alfalfa genotypes which did not survive frequent cuttings did not have the capacity to restore TNC to storage sites as quickly as did those that survived frequent cutting. They suggested selection of genotypes that produce new tillers early in the regrowth cycle.

Both alfalfa and red clover produced three separate growths from the crowns in Wisconsin during a growing season when left uncut; in contrast, birdsfoot trefoil produced no new growth from the crowns or lower axillary buds after early spring when it was left uncut (regrowth came from upper axillary buds on old stems) in studies by Smith (1962) and Nelson and Smith (1968). Alfalfa maintained the highest level of TNC reserves, followed by red clover; birdsfoot trefoil maintained very low TNC reserves throughout the growing season.

Regardless of the specific mechanism that allows regrowth of grazed legumes, we know that prolonged defoliation (such as occurs in continuous grazing or in rotational grazing more frequently than 4 to 6 weeks) is detrimental to long-term persistence of all legumes adapted to the Northern United States. But, because decumbent species (such as white clover or kura clover) maintain greater leaf area at ground level during grazing, they can survive frequent or continuous grazing longer than can erect species such as alfalfa or sweetclover.

Brink and Marten (1983) reviewed research from the 1950's to 1970's that led to the conventional wisdom that alfalfa should not be cut in the northern part of the United States during an autumn growth period between early September and early October (until killing frost) or not at all after the first week of September to avoid stand depletion. This recommendation was based largely on a body of research reviewed by Walgenbach (1983) that supported the hypothesis that stored TNC is crucial to winter survival of alfalfa and that a high level of TNC should be accumulated before winter to develop a high degree of winter hardiness, to maintain winter-hardened plants through the winter, and to initiate growth the following spring. Walgenbach concluded that many factors can influence the persistence, productivity, and quality of alfalfa cut during the "critical" autumn period. He presented a list of autumn cutting recommendations based on his judgment of the order of increasing risk to loss of stand and yield that might be expected when alfalfa in the Northern United States is harvested after early September. Least risk was by cessation of cutting during or after the 4- to 6-week "critical" period; greatest risk was indiscriminate harvest during this period regardless of stage of development, fertility level, winter hardiness or disease resistance of the cultivar, and snow cover. These recommendations were supplemented by evidence presented by Brink and Marten (1983) which showed that the length of the harvest interval during the growing season is very likely more important than the final autumn harvest date in determining alfalfa survival over winter. They confirmed the earlier results of Marten (1980), Tesar (1981), and Sheaffer (1983) which showed that a third cutting during the "critical" autumn growth period following first cut in early summer (about June 1) and second cut in midsummer (about July 15) will very likely not cause alfalfa stand depletion, provided a winter-hardy and disease-resistant cultivar is used with high soil K fertility and adequate snow cover during the coldest parts of the winter. Cutting of alfalfa four times at frequent intervals either before September 1 or before the first killing frost in autumn in this same area has usually caused severe stand depletion within 2 years.

Properly managed alfalfa was reported to persist for 34 years on certain rangeland sites in the Western United States (Marten 1981).

Red clover produced yields equal to those of alfalfa in Wisconsin only when both were harvested by use of a "conservative" two-cutting schedule (full bloom stage or beyond) in an experiment by Smith (1965). However, alfalfa yields were highest when three harvests were each taken at early flower stage. Smith concluded that red clover was at best a two-cutting legume, because yields were reduced with greater cutting frequencies. However, Taylor and Smith (1981) stated that the first crop of red clover should be harvested at either prebloom or early bloom for the best compromise between forage yield and quality. Then subsequent harvests as hay or pasture should be made at 6- to 7-week intervals, including a harvest after autumn freezing if sufficient growth is available.

The amount of stubble left after cutting is more important to maintenance of vigorous stands of birdsfoot trefoil than it is to maintenance of alfalfa (Smith and Nelson 1967). This could be because TNC root reserves in birdsfoot trefoil

remain at a low level during the growing season even if crops are not cut; therefore, a tall stubble provides the green leaves needed to produce photosynthetic energy that is needed for birdsfoot trefoil regrowth, whereas alfalfa can rely on root reserves. They found that stubble height in alfalfa became important only when cutting was so frequent (six times per season in Wisconsin) that TNC storage was limited or when very low light intensity (glass-house) limited full photosynthetic activity.

Research Needs

More research is needed concerning the influence of climatic variables and climatic changes within and among seasons on basic physiological processes within and among forage legume species. For example, we need to know whether water-use efficiency, especially during periods of moisture deficit, can be modified by genetic selection or by management while economic yield is simultaneously increased or maintained. Research to overcome susceptibility to moisture excesses would be greatly beneficial. Also, we need to overcome the major barriers to long-term persistence of forage legumes (such as root-rot complex and winter injury) via a better understanding of the physiological and morphological mechanisms of stand depletion. The interactions of genetics and environment involved in persistence problems (e.g., the influence of environment on "internal breakdown" and earliness of disease attack in red clover genotypes) must be determined to accomplish this. We also need a more complete understanding of the morphological phenomena associated with initial spring growth and regrowth after harvest of forage legumes (e.g., the rates of bud initiation and tiller production).

The physiological and morphological factors that are operable during grazing vs. cutting of legumes may differ. We need to know how and why so that we can more effectively utilize individual species or cultivars for specific components of total management systems. Competition, allelopathy, and/or synergism among companion species in legume mixtures or legume-grass mixtures are not well understood, even though we know that they vary depending upon environment.

More research is needed on seed production problems of alfalfa to overcome recent reduced yields and provide economic stability to the industry (e.g., pollination and pest control problems). The possibilities for genetic selection or improved cultural or chemical methods to increase the partitioning of photosynthate to seed, to produce a more determinant growth habit, or to increase dehiscence resistance in birdsfoot trefoil should be investigated to improve seed yields and harvests.

Investigations are needed to determine whether pesticides can be efficiently used to control mollusks, insects, and nematodes that preferentially attack seedlings of certain legume species and cultivars during minimum tillage pasture renovation. We need to improve the seedling vigor and establishment of some initially noncompetitive legumes such as birdsfoot trefoil, cicer milkvetch, crownvetch, kura clover, and zigzag clover.

The potential role of specific forage legumes in complete production systems has not been adequately determined; species that have inferior yield may have superior quality or superior persistence or fill a special purpose need in certain environments so that they have a greater-than-now-realized value in supplementing current forage-livestock systems.

The need for constant alertness to detect and control old and new pests of forage legumes endorses the wisdom of a research effort in integrated pest management that is never terminated. Some well-recognized pests like potato leafhopper are not yet adequately controlled by plant resistance (which suggests need for continued breeding effort). Among insect pests that have recently spread in their attack of alfalfa in northern regions are the blue alfalfa aphid [*Acyrthosiphon kondoi* (Shinvi)], alfalfa weevil, meadow spittlebug, and alfalfa blotch leafminer. Among diseases that have recently caused concern are *Verticillium albo atrum* Reinke Bertl., *Phytophthora megasperma* Drechs., and *Pratylenchus penetrans* (root-lesion nematode). New weeds are also continually moving into localized areas, which mandates a continued research program in weed control.

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Discussion

Rumball: Do you have well-adapted lucerne cultivars?

Marten: Yes, they are well suited to the 20°-25°C temperatures which prevail during the main part of the growing season.

Knight: There has been a very large proliferation of lucerne cultivars so that over 60 are now commercially available. This is causing problems of seed availability and increasing production costs.

Marten: The fact that the numbers continue to increase suggests that there is a market for a greater range of cultivars.

Brougham: In the United States, management in the fall appears important in winter persistence. In New Zealand, we graze hard prior to winter. Why is there such a difference? Also, how difficult is it to control leafhoppers?

Marten: The major factor involved in winter survival of legumes is how well developed the hardening process is when the cold period arrives. The depth of snow cover as well as the consistency of snow cover is also important. Resistance to pests and high soil fertility, especially high K levels, are also important to winter survival in our environment. You have a milder winter in much of New Zealand, so these factors may be less important for you.

The lack of success in breeding programs shows how difficult control of leafhopper is. Perhaps we require a wider germplasm base. Now we must rely on insecticides and timely harvest to control leafhoppers.

Syers: Why no mention of soils in your list of nine areas for research needs?

Marten: This is purposeful because the edaphic factors will be covered by the U.S. speaker on soils. Lack of proper soil fertility is a very important constraint to alfalfa production.

Reed: Is there any use of coated seed in the United States to kill or deter pests?

Marten: Pesticide-coated seed has not usually been effective. However, more research is being done on this subject--especially for minimum tillage (sod-seeding) operations.

Environmental and Management Limitations of Legume-Based Forage Systems in the Southern United States

J.C. Burns[1]

Abstract

In the humid south the perenniality of all legumes is greatly reduced because of a heavy insect and disease burden. Combined, these pests form such a formidable complex that stands of the most persistent perennial cool-season legume cannot be expected to persist beyond the third summer (including the year of establishment). The major perennial legumes that contribute significantly to legume-based systems are white clover (Trifolium repens L.), red clover (Trifolium pratense L.), alfalfa (Medicago sativa L.) and sericea lespedeza [Lespedeza cuneata (Dumont G.) Don]. Crimson clover (Trifolium incarnatum L.), hairy vetch (Vicia villosa Roth.) and arrowleaf clover (Trifolium vesiculosum Savi.), being winter annuals, make important contributions during the late fall and mid to late winter. The annual lespedezas [L. striata (Thunb.) Hook and Arn. and L. stipulacea Maxim.] make contributions during the midsummer. Birdsfoot trefoil (Lotus corniculatus L.) offers some potential but is presently grown on only limited land area. Site selection and management practices can help prolong stand survival on a short-term basis (up to 3 years). The major problems limiting legume-based systems and research needs are discussed.

Introduction

Given favorable climatic conditions and soil-plant nutrient status, the productivity of forage grasses in the Southern United States is directly related to the amount of nitrogen (N) available. Without N fertilization of grasses or the use of legumes in mixtures with grasses, dry-matter yields of slightly over one metric ton ha^{-1} would frequently occur. On better soils, yields may surpass two metric tons ha^{-1} (Templeton 1978).

Pure grass stands obtain supplemental N from several sources: (1) Mineralization of soil organic matter, (2) precipitation, (3) fixation by free-living organisms, (4) symbiotic fixation, or (5) fertilization (Templeton 1978). Sources 1, 2, and 3 contribute to the productivity of most grasslands, but highest yields result from either symbiotic fixation using legumes or from nitrogen topdressing.

From the early 1950's through the early 1970's, fertilization of grass pastures with N was attractive in the humid south (east Texas to the east coast) because of relative N costs, labor-management consideration, and sale of animal products. Since the early 1970's, relative costs have shifted. The high cost of N (fivefold to sixfold increase) has placed more emphasis on legumes for supplying N to maintain high forage yields and to improve forage quality (higher animal daily response).

Important Legumes for Legume-Based Forage Systems

The single most important perennial legume used in pasture environments in the Southern United States is white clover (Trifolium repens L.). The giant ladino types predominate in the Upper South, while in the Deep South the intermediate, heavy reseeding types predominate. The low-growing (white dutch) ecotype is found throughout the Appalachian Mountain region at the higher elevations.

Red clover (Trifolium pratense L.) is frequently used in mixture in the Upper South, (Blaser et al 1969). It generally persists only 2 years, but under some conditions a third year production can be obtained. Red clover is well suited for sod-seeding because of its excellent seedling vigor and vigorous growth the year of establishment. However, stand thinning is evident by the second year of use, and stands are generally depleted by the third. Lack of perenniality of red clover requires continuous reseeding. This is accomplished with annual surface applications of seed by sod-seeding each year or every other year.

Alfalfa (Medicago sativa L.) is the major hay legume in the Southern United States, although hectarage is limited. Major production occurs in the Upper South and on some of the heavy-textured, well-drained soils in the deeper South. Most alfalfa is grown in pure stand with initial growth harvested at the early bud stage and regrowth harvested every 4 to 5 weeks, usually in the early-bloom stage. New cultivars are better adapted to the southern environment, showing less winter hardiness than germplasm from farther north but greater tolerance to insects and diseases. Consequently, new cultivars may be more resilient and persist better under grazing. Past cultivars were generally lost during the second year of grazing even when using a rotational scheme.

Birdsfoot trefoil (Lotus corniculatus L.) is receiving increased attention as a potential perennial legume in the South. However, its present hectarage is quite small. Recently released cultivars from Kentucky (Fergus) and Alabama (AT-P) appear better adapted. Its potential is demonstrated by northern Alabama trials where a pure stand of an introduced cultivar (San Gabriel) produced over 6,500 kg ha^{-1} in the fourth year after establishment (Hoveland et al. 1982) In contrast, red clover yielded over 5,600 kg ha^{-1} the third year, but complete stand losses occurred by the fourth year.

Sericea lespedeza [Lespedeza cuneata (Dumont G.) Don] is the only perennial legume in the South that makes an important contribution to legume-based forage systems during the midsummer period. Large hectarages of perennial lespedeza were planted in the Deep South during the 1930's and 1940's because of tolerance to acid, low fertility, and deep sandy soils and resistance to most insects and diseases. Although tolerant of low fertility, the crop is

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responsive to fertilization, producing yields of over 4 metric tons ha^{-1} (Guernsey 1970). Young and succulent forage provides satisfactory midsummer pastures (Hoveland et al. 1969). Generally, high fiber concentrations and the presence of tannins have permitted only moderate animal performance (Cope and Burns 1971). Because of this, hectarage has declined greatly in recent years. The recent development of low-tannin lines should improve the quality aspect (Donnelly et al. 1971).

A number of annual forages are used in the South and make a substantial contribution. The two most important annual clovers are crimson (Trifolium incarnatum L.) and arrowleaf (Trifolium vesiculosum Savi.). Both make an important contribution to the livestock industry by extending the grazing season and supplying good yields of high-quality forage during the winter and early spring (Hoveland and Evans 1970). Hairy vetch (Vicia villosa Roth) is also widely used in the Deep South and west into Oklahoma and can serve as a substitute for annual clovers. They are seeded alone or in mixture with annual grasses in the fall and frequently into dormant, subtropical pastures. In late spring they are allowed to seed if stands are desired the following winter. A large percentage of hard seed is produced and escapes germination until fall rains begin. Germination occurs over an extended period in the fall, generally resulting in acceptable stands. Reestablishment depends strictly on reseeding, so the aspect of perenniality is moot.

The two annual lespedezas [L. striata (Thunb.) Hook and Arn. and L. stipulacea Maxim.] also make contributions. They are spring-seeded and used during the summer for hay or grazing. Growth begins slowly, with the first hay harvest ready by August. If stands are desired the next season, plants are either cut early for hay or cattle are removed from pasture so that regrowth will head and reseed, or initial haying is delayed to allow adequate seed shatter for reseeding (Henson and Cope 1964). The latter practice results in extremely low-quality hay. The hectarage of annual lespedeza has declined in the South, but these species often persist as background species in many pastures.

Major Factors Limiting Use of Perennial Legumes

Pests and Persistence

Once legume stands are established, the most important factor limiting their use in legume-based forage systems is their persistence. The lack of persistence of the more important perennial legumes (white clover, alfalfa, red clover, and birdsfoot trefoil) is apparently due to an insect-disease complex (insects, fungi, viruses, and nematodes). Some appreciation for the magnitude of the problem can be obtained from the list of pests shown in tables 1 and 2. Even with general grouping for certain pests, there are 13 shown for insect types and 23 diseases induced by bacteria and fungi, 18 by viruses, and 4 by nematodes. Excellent discussions on each pest and type within pest are presented by Barnett and Diachum (1984), Manglitz (1984), and Leath (1984) for the clovers and by App and Manglitz (1972) and Graham et al. (1972) for alfalfa.

Although stands can be depleted by severe infestation of a single pest, generally no one pest is sufficiently devastating in the field to cause complete stand failure. The importance of any one type of insect or disease is difficult to determine, as insect population and disease outbreaks are highly dependent on climatic conditions and edaphic factors that vary greatly from location to location and from year to year within locations. Also, existing strains of unidentified pathogens further complicate the problem. An example is the recent isolation of a highly virulent isolate (NC-4) of anthracnose (Colletotrichum trifolii) from a diseased anthracnose-resistant alfalfa plant. The new isolate was far more virulent than known isolates from North Carolina and Pennsylvania (Welty and Mueller 1979).

Natural insect populations generally consist of the foliage feeders, sap suckers, and root and stem feeders listed in table 1. Their damage provides avenues of entrance for diseases, and they also act as disease transmitters (Manglitz 1984 and Graham et al. 1972). The aphids are the major vectors of the nonpersistent viruses and will frequently transmit several viruses to the same plant (App and Manglitz 1984 and Barnett and Diachum 1984). The total burden on the plant from defoliation and weakening by insects and the insidious presence of the viruses, collectively, reduce growth and survival under stress conditions. Further, root diseases, root-feeding insects, and nematodes cause continuous pruning and weakening of the root system. This above- and below-ground complex places the legume plant in a very untenable environment.

Peanut stunt virus (PSV) reduced numbers of nodes of primary stolons, petiole length, and length of longest roots in white clover. Combining PSV and alfalfa mosaic virus (AMV) reduced numbers of rooting nodes of primary stolons, number of secondary stolons, and number of leaves per plant. Including clover yellow vein virus with PSV and AMV reduced the length of primary and secondary stolons, number of rooting nodes in secondary stolons, and leaf and stolon dry weight (Barnett and Diachum 1984).

This total complex accounts for field observations of unproductive and unhealthy legumes. Many plants will survive the burden of the complex if environmental conditions are mild. However, imposed stress (such as frequent defoliation or drought) results in rapid death and total stand depletion. The pruning of the root system of birdsfoot trefoil by root-knot nematodes present in Alabama soils provides some measure of such stress. Control and methyl bromide treatment gave respective first-year dry matter yields of 7,160 and 8,461 kg ha^{-1}, but second-year yields were 0 and 3,463 kg ha^{-1} (Hoveland et al. 1982). Persistence was little better farther north in Missouri when trefoil plants survived about 2 years regardless of pasture, hay, or stockpiled management (Beuselinck et al. 1984).

The concept of multiple pest resistance is being practiced in breeding programs (Devine et al. 1977). Varying levels of tolerance to many of the pests listed in tables 1 and 2 exist in world germplasm pools and can be incorporated into

Table 1 - Insect and disease pests that alter productivity and persistence of legumes in the Southern United States

I Insect types[1]	II Diseases (bacterial and fungi)[2] Common name	Conditions[3]	Losses[4]
Forage consumers:	Bact. blight, wilts; leaf spots	C, M	..
Alfalfa weevil	Black patch	Wr, M	L
Beetles	Curvularia leaf spot	Wr, W	L
Caterpillars	Fusarium wilt	Wr, LD	L
Clover leaf weevil	Leptosphaerulian leafspot	C, W	..
Grasshoppers/crickets	Mildews (powdery, downy)	WD, CN	S
Slugs	Myrothecium leaf spots	W, W	L
Sap suckers:	Northern anthracnose	C, M	S
Aphids	Phytophthora root rot	L, W	L
Leaf hoppers	Pseudopeziza leaf spot	C, M	..
Meadow spittle bug	Pythium root rot	L, W	L
Spider mite	Rhizoctonia foliar blight	H, M	S
Root and stem feeders:	Root and crown rot complex	C	S
Clover root borer	Rust	....	S
Clover root curculio	Sclerotinia rot	C, W	..
Less important beetles	Seedling blight	....	..
	Sooty blotch	L, W	L
	Southern anthracnose	C, M	..
	Southern root and stolon rot	....	..
	Spring black stem	WD	S
	Stagonospora leaf spot	....	..
	Stemphylium leaf spot	....	S
	Verticillium wilt	....	L

[1]Adapted from Manglitz (1984) and App and Manglitz (1972).

[2]Adapted from Leath (1984) and Graham et al. (1972).

[3]C = cool; M = moist; WR = warm; W = wet; LD = long day; WD = warm day; CN = cool night; L = low; and H = hot.

[4]L = light; S = severe.

Table 2 - Viruses and nematode pests that alter productivity and persistence of legumes in the Southern United States

I Viruses[1]			
Common name	Transmitted	Persistence[2]	II Nematodes[3]
Alfalfa mosaic	Aphid	N	Root-knot
Bean yellow mosaic	Aphid	N	Root-lesion
Clover enation	Aphid	P	Clover cyst
Clover yellow mosaic	Contact	..	Stem
Clover yellow vein	Aphid	N	
Cucumber mosaic	Aphid	N	
Legume yellows	Aphid	P	
Pea enation mosaic	Aphid	P	
Pea leafroll	Aphid	P	
Pea streak	Aphid	N	
Peanut muttle	Aphid	N	
Peanut stunt	Aphid	N	
Red clover vein mosaic	Aphid	N	
Tobacco necrosis	Fungi		
Tobacco ringspot	Nematode		
Tobacco streak	Unknown		
Tomato spotted wilt	Thrips		
White clover mosaic	Seed		

[1]Adapted from Barnett and Diachum (1984) and Graham et al. (1972).

[2]N = nonpersistent, and P = persistent.

[3]Adapted from Leath (1984) and Graham et al. (1972).

varieties (P.R. Beuselinck, personal communication; Hunt et al. 1972; Kehr et al. 1972; Sorensen et al. 1972; Donnelly 1983; and Cope 1984), if given adequate priority. The present effort devoted to legume germplasm introduction and enhancement in the Southern United States is totally inadequate relative to the task at hand.

White clover, red clover, and the annual clovers are each receiving the efforts of only one full-time breeder while alfalfa, lespedeza, and birdsfoot trefoil are receiving little or no consideration. Further, no structured effort to obtain new sources of germplasm for legumes in the South is known other than from occasional finds from collection trips having other purposes. Under present programming and planning, the likelihood for legume improvement in the South is bleak.

Seed Availability

A problem associated with cultivar improvement is an inability to obtain an adequate seed supply in programs involved in cultivar improvement or when improved cultivars are released. A case in point is the improvement of birdsfoot trefoil for the South. Southern cultivars need less winter hardiness but more pest tolerance. However, high-quality seed and high seed yields are obtained only in northern latitudes where winterkilling of southern adapted cultivars becomes a problem (P.R. Beuselinck, personal communication). Often fair or average cultivars can become widely grown purely because they are good seed producers.

Seed availability of improved cultivars is also a serious problem. Seed of the most recently released ladino clover cultivar 'Tillman' (release from South Carolina in 1965) was not available in the Southeast for the 1983 fall planting season. Also, a new cultivar of birdsfoot trefoil released from Alabama is not commercially available. Neither the public nor the private sectors are adequately fulfilling this important need. Improvement programs are of limited value without channels for proper seed exchange and adequate supply.

Stand Establishment

The third most important factor limiting legume use in legume-based systems of the Southern United States is lack of consistency in obtaining acceptable stands. White clover, red clover, alfalfa, and birdsfoot trefoil seedings can be made in the South in either the fall or spring. Fall seedings are generally more successful because of reduced competition from grass and broad-leaved weeds. However, spring seeding, especially in the upper south, is practiced and can be successful (Blaser et al. 1969, Mueller and Chamblee 1984).

Legume establishment can be achieved either in a prepared seedbed or by direct seeding into an existing grass sod (sod-seeding). Both practices have problems unique to the situation. In the Middle South, fall seeding into a prepared seedbed is best made in late August through early September. Seeding into a dry seedbed that has been well prepared is recommended as opposed to waiting for conditions that will allow preparation of a seedbed with adequate moisture. Fall rains, as thunderstorms, generally begin in early September and continue through mid-October. However, rainfall can be extremely variable, causing frequent reductions in legume stands and even failures. Light showers may initiate germination. Unless another shower follows soon (3 days), the high daily temperatures cause drying of the top 6 to 12 mm, causing reduced stands or failures. The other extreme of brief periods of intensive rainfall causing severe surface erosion and crusting also results in poor stands. A third problem is prolonged periods of drought that result in delayed germination of seed, inoculation failure, and subsequently poor winter survival.

A prepared seedbed reduces the major insect and plant competition. However, annual broad-leaved weeds can become a problem by early spring and may need to be clipped as forage growth begins in early March. Seeding in a prepared seedbed after October 15 to 20 frequently results in failure, as plants do not become adequately established, and appreciable winterkilling results from cold exposure. However, most losses are due to soil heaving and desiccation of exposed roots (Rogers et al. 1983a). The presence of annual broad-leaved weeds in this case can be beneficial if they are not too dense (competition for light) by providing some buffer to winter exposure and heaving (Cope et al. 1973).

The alternative method of establishment by sod-seeding is receiving renewed attention because of reduced establishment cost and less opportunity for soil erosion. This practice can yield extremely variable results ranging from highly successful to nearly total failures. In the Middle South, excellent stands have been obtained experimentally when consideration was given to seeding date, competition from existing sod and potential damage from insects present in the sod. Rogers et al. (1983b) found these factors to have a striking effect on yields the year following fall seeding of ladino clover into tall fescue when moisture stress and high insect populations (crickets, grasshoppers, leafhoppers, and armyworms) occurred (table 3). The use of either paraquat or an insecticide alone or together for a September seeding gave striking increases in both legume and total mixture yields. Delaying sod-seeding until 20 October when insect populations had declined showed the insecticide to be of little value, while paraquat reduced competition and improved legume yields. Total mixture yields were similar for all treatments. In contrast, late seeding in a prepared seedbed resulted in excellent stands where the sod had been thinned to allow light penetration. The sod apparently acts as an insulator for the clover against winter exposure and heaving. Most plants (from the mid-October seedings) were in the single trifoliate leaf stage by early December. Studies with alfalfa produced similar results (Rogers et al. 1982).

Seeding white clover in the spring into tall fescue sods was superior to spring surface seeding the first growing season, but no difference was noted by the second year. A February seeding date was superior to March. Spring seeding of alfalfa was

Table 3 - Paraquat and insecticide (carbofuran) effects on ladino clover-tall fescue dry matter production (kg ha^{-1})

Treatments	Seeded September 7		Seeded October 20	
	Clover	Mixture	Clover	Mixture
Check	183	3,780	3,550	6,410
Paraquat (P)	2,564	6,510	5,767	6,908
Insecticide (I)	1,079	4,496	4,036	7,609
P + I	5,568	8,871	6,669	7,656

[1]Adapted from Rogers et al. (1983b).

not satisfactory for either date due apparently to competition between seedlings and the fescue sod (Mueller et al. 1984).

Management Practices That Improve Stands and Prolong Longevity of Legumes in Mixed Stands

Prolonging legume survival in the long term (beyond 3 to 4 years) can only be achieved through improved pest-tolerant varieties (see above). However, in the short term (up to 3 years) legume stand survival can frequently be extended into the third year by certain management practices.

Site selection can be an important factor in both legume establishment and persistence. Ideal characteristics are a deep and well-drained soil with high water-holding capacity, pH in the range of 6.0 to 7.0, a high nutrient supply (particularly of P and K), and no chemical or physical impediments to root penetration (Blue and Carlisle 1984). Most soils do not have all of these characteristics, but many can be amended chemically at establishment. Generally, soils limed to above pH 5.5 will decrease the Al^{3+} to nontoxic levels and increase availability of Ca and Mg. Seeds of best-adapted cultivars should be used, properly inoculated with the appropriate Rhizobium species, and placed to a proper depth in the soil. Surface-placed seed may die before establishment, and seed placed below 19 mm may not emerge.

After establishment, legume stands can be prolonged and made more productive through application of nutrients and proper defoliation practices. In general, annual applications of P and K, and in some cases S and B, are required in the South. The coarse-textured soils in the southeastern Coastal Plains may also have deficiencies of Co, Cu, Fe, Mn, an Zn, especially as pH is increased above 6.0 (Blue and Carlisle 1984).

Judicious defoliation practices can be extremely useful in retaining legumes in mixture with grasses. Close defoliation (12 to 25 mm) favors white clover stands (Robinson and Sprague 1947). Clovers appear to have three types of regrowth strategies. Red clover and alfalfa depend on reserve assimilates for regrowth with an associated top growth suppression of new lateral bud development. White clover utilizes reserve carbohydrates under infrequent defoliation where a significant deposit of nonstructural carbohydrate accumulates in the stolons. Under frequent defoliation, the dependency for assimilates shifts to current photosynthesis from the remaining leaves (Kendall and Stringer 1984).

Management factors involve leaf area, carbohydrate reserves, and shoot initiation (Blaser 1974). Close defoliation in early spring reduces the competition from grass by allowing penetration of light into the canopy favoring clover growth (Sprague and Garber 1950). Further, close defoliation of grass results in removal of some carbohydrate reserves (stems) and reduced leaf area. Subsequent regrowth is reduced because of lower carbohydrate reserves. White clover is favored because new growth originates at the base of the stolon, which is not removed by defoliation. Close defoliation in spring and fall favors clover in mixture, but close grazing in summer can be detrimental to clover stands. In clover-dominated stands, lax grazing in spring and fall results in a high grass leaf area and reserve carbohydrate status. This causes rapid regrowth of the grass, reduced light penetration near the soil surface and inhibition of leaf and shoot development of clovers. Clover thinning follows. Avoidance of large accumulations of forage reduces the buildup of insects and diseases and causes less stress on plants.

The importance of insects and diseases is clearly shown in a five-year study by Chamblee et al. (1981) where a ladino clover-tall fescue (Festuca arundinacea Schreb.) stand was either untreated or treated with a fungicide (F), insecticide (I), and both (F+I). Respective yields in metric tons ha^{-1}, followed by associated clover percentage (in parenthesis) for the first year were: 7.7 (47), 7.5 (47), 8.4 (52), and 9.7 (67). By the third year, respective values were: 2.8 (7), 5.4 (25), 5.2 (32) and 8.0 (77). Both the F and I maintained legume stands longer and produced greater dry-matter yields than the control. However, best results occurred when both disease and insects were controlled (F+I). This important study shows the significant role pests play in reducing the legume component

(47% to 7%) and subsequently total yields (7.7 to 2.8 metric ton ha^{-1}) of mixtures. Applying the F and I together retained both high yields (8.0 metric ton ha^{-1}) and legume stands (77%) in the mixture.

Contrary to clovers, alfalfa is usually grown in pure stands in the South and harvested as hay or haylage. Stand persistence can be improved somewhat by appropriate management practices (Leath 1981). In addition to the general practices noted for legumes above, chemical control of the alfalfa weevil and an appropriate harvesting schedule are probably the two practices most helpful in extending stand survival. A recommended harvest schedule in the Middle South is to harvest first growth in the early to midbud stage followed by regrowth harvest in early bloom. Harvests can be taken every 4 or 5 weeks with four to five harvest obtained during the growing season. This schedule removes accumulated forage frequently enough to minimize excessive disease and insect buildup, but allows adequate time between harvests to restore depleted carbohydrate reserves used in the early phases of regrowth (Smith 1975).

Research Needs

Information on successful use of legumes in the Southern United States clearly points out that the major research need is to develop improved persistence in all presently grown species. Sericea lespedeza may be an exception; however, low-tannin lines are more susceptible to disease attack (Donnelly 1983). Significant advancement appears related to the development of multiple-pest-resistant cultivars. These must be well adapted from the Upper to the Lower South and from East to West. Such development will require a team initially composed of scientists representing the problem area limiting plant survival. This effort must include the introduction of new germplasm. This might occur from traditional collection and plant introduction programs that can supply new germplasm for plant-breeding efforts or through some aspect of biotechnology as the latter area develops.

Another area of research, related to the above, is continued studies on the approaches and methods of reliable establishment of legumes either in a prepared seedbed or by direct seeding into a sod. Of major importance is inoculation and seedling vigor. The latter involves actual growth rate of both the roots and tops and their competitiveness with grasses and other weedy species.

Further data and more understanding are needed on defoliation management relative to physiological factors that alter stand persistence. This will become even more important as improved cultivars are developed and released.

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Discussion

Brougham: In South Africa, a deep-rooting white clover has been selected. I suggest you obtain some seed for use in the Southern United States.

Burns: I agree, we need to introduce more variation into our germplasm in general.

Knight: The major problem is that we have not had the specialists in nematology, virology, and pathology to identify why clovers do not persist.

Burns: We need the specialists, but we also need to evaluate a lot more new material.

Knight: In 1966, a cultivar of arrowleaf clover was released to overcome some problems with crimson clover. Today, arrowleaf clover has three major viruses, two root rots, stem borer, and is affected by nematodes. Unless we solve these problems with a crash program, arrowleaf clover will disappear.

Sheath: Is there actually a need for legumes by individual farmers in the Southern United States?

Burns: Yes. However, the animal enterprise is generally not the sole production system on a farm as in New Zealand, but legumes are important just the same. The argument that a N-grass system might be easier for a part-time farmer is valid, and does play a role.

Minson: How many people in the United States are involved in breeding for tolerance or resistance to pests in alfalfa?

Marten: Too few. There are fewer today than a few years ago. Survey results as to exact numbers are available.

Helyar: A problem is that for individual pest resistance to be selected for by breeding, a lot of work is required for species which are utilized in relatively small areas. Two alternatives are to focus on major species only or to move towards an increased use of mixtures.

Knight: Large areas of the Southern United States will never grow alfalfa. Resources have to be used for other legumes.

Sheath: In New Zealand, we have generally decided to live with pests and let natural selection occur in particular ecosites. Why is it different in the United States?

Burns: In the United States, we are dealing with a monoculture or at best a two-species mixture, and we can not afford to ignore pests.

Field: Timing of defoliation of alfalfa is mentioned as important. Are there defined procedures or models for determining first bud, etc.?

Marten: There are three alfalfa models for predicting plant and animal responses to defoliation. These have been developed at Cornell University, Ithaca, New York; Purdue University, West Lafayette, Indiana; and University of Kentucky, Lexington, Kentucky.

Nitrogen Fixation by the Legume-Rhizobium Symbiosis: The Role of the Bacteria

R.J. Roughley[1]

Abstract

The role of the root-nodule bacteria in the legume symbiosis is two-fold. They initiate legume root infections which stimulate the host to form nodules providing the appropriate conditions for N_2 fixation. They also carry the genes for nitrogenase and for the haem moiety of the leghaemoglobin molecule. To accomplish these functions the bacteria must be able to survive in the soil and colonise the rhizosphere under environmental conditions which may be unfavourable. The effects of some components of the physical and chemical environment on their survival and movement in soil are described. Rhizobia infect legume roots by one of two routes; namely, invagination of the host's root hairs, or by direct entry of the root where lateral roots emerge. The mode of entry is determined by the host plant and this may be directly related to its specificity.

Rhizobia may be very variable in culture and this is discussed in terms of their agricultural exploitation. It is now known that the symbiotic genes of the fast growers are plasmid located and this may explain their capacity to revert to Nod^- or Fix^-. The progress in Rhizobium gene manipulation raises the possibility of strain construction in the future but the construction of deficient mutants is already aiding our understanding of the genetical basis of observed events in the establishment and functioning of the symbiosis.

The problems of introducing improved strains into soil and the role of seed inoculation are discussed.

Introduction

In most agricultural systems the nitrogen demands of the plant are greater than that supplied by the soil nitrogen pool. This deficit may be met by fixing nitrogen, i.e., by breaking the triple bonding of pairs of nitrogen atoms to make them more reactive. This may be done industrially, a process which is very energy demanding, requiring temperatures between 300-600°C and pressures of 20,000-80,000 k Pa. Biological fixation requires only ambient temperatures, but it too has an energy cost which must be met by the host plant either indirectly with free-living N_2-fixing micro-organisms or directly in symbiotic systems. A legume may range from being fully dependent on soil nitrogen when either unnodulated or ineffectively nodulated through partial dependence on fixed nitrogen at moderate levels of soil N to full dependence on fixed N when soil N is low. The resulting effect of growing the legume on the soil N status will depend on the relative contributions from the soil N and fixed N during its growth, and the proportion of nitrogen in the crop which is removed or re-cycled by grazing animals.

The role of the bacterium in the legume symbiosis is two-fold. It firstly is the means of infecting a legume root and initiating a nodule which will provide the required physiological conditions for N_2-ase expression and secondly it acts as a carrier for the genes coding for N_2-ase production and the production of the haem moiety of the leghaemoglobin molecule (Dilworth and Appleby 1979). In accomplishing these roles it must successfully negotiate a number of pre-infection and infection steps on the way to initiating a nodule. During these steps the bacteria are exposed to the physical, chemical, and biological environment of the soil which often is unfavourable for their survival, multiplication, and migration. There has therefore been considerable research into ameliorating adverse conditions and selecting strains of rhizobia which are more resistant to them. This has led in turn to attributing a greater importance to the Rhizobium than to its legume host. More recently this has been seen as a distorted view and the important role of the plant in providing the energy to drive the system has been widely recognised.

Pre-Infection Phase

Rhizobium as a Soil Saprophyte

In the soil, rhizobia live as a component of the soil heterotrophic micro-organisms and reach their greatest numbers in the rhizosphere. They are stimulated by exudation of nutrients from plant roots and are controlled to some extent by competition, antagonism, lysis, and predation by other micro-organisms and by their physical and chemical environment. It is their ability to infect legume roots and subsequent multiplication within the host plant, where they are protected to some extent, and their later release into the soil which gives them a particular advantage.

Because Rhizobium species cannot be distinguished unequivocally in cultures, knowledge of their behaviour in soil is surprisingly limited. Until recently, counting rhizobia in soil has been restricted to most probable number methods (M.P.N.) requiring a trap host plant (Vincent 1970), and even now it is the only relatively simple method to count numbers of naturalised rhizobia. Numbers of introduced strains may be counted on agar containing antibiotics provided they carry a recognisable marker (Bushby 1981).

Spatial distribution of rhizobia in soil may be determined by sectioning a soil core into segments and counting the rhizobia in each segment, or, alternatively, it is possible to examine the distribution of a particular strain by immunofluorescence (Schmidt 1974).

To perform their role in initiating root infection, rhizobia must be present in high numbers in the rhizosphere. It is important therefore to briefly consider some of the more important factors which

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may limit the rhizosphere population (see review Parker et al. 1977).

Effects of Soil Temperature and Moisture

Survival of Rhizobium in soil is adversely affected by high soil temperatures. The effect is modified by the soil type; survival is better in heavy or organic soils than in light soils. Survival in light soils may be improved by amendments including montmorillonite and illite which probably reduce the amount of water loss from the bacterial cell (Marshall 1964). Rhizobia are less tolerant of high temperatures in moist than in dry soils.

As would be expected there are differences between strains in tolerance to high temperatures even when selected from soils of the same region subjected to similar soil temperatures.

Although populations of rhizobia may be quite small at the surface, numbers may reach high levels down the profile depending on ground cover and soil type.

There is little information on the effect of low root temperatures on rhizobia in soil. Strain differences have been clearly demonstrated in the ability to infect, nodulate, and fix nitrogen. In one study, R. trifolii TA1 grew well in the rhizosphere of T. subterraneum at 7°C yet failed to infect the root hairs at populations equivalent to those which could infect at 19°C (Roughley et al. 1970).

Although the poor survival of R. leguminosarum in flooded soils is well known, the effects of soil hydration on nodule formation have been neglected. Other species of Rhizobium may be more tolerant of periods of anoxia; there is certainly considerable variation in their ability to survive dry conditions, e.g., R. trifolii is more tolerant of drought than either R. meliloti or R. lupini, and the slow-growing strains are more tolerant than fast growers. There is no correlation between ability to grow in dry soils and resistance to desiccation.

Infection of root hairs by rhizobia may not occur in dry soil, even though numbers in the rhizosphere are unaffected (Worrall and Roughley 1976).

Effects of Soil Acidity Factors

Species of Rhizobium respond differently to acidic and alkaline soil conditions. Generally, slow-growing rhizobia which nodulate tropical legumes are less sensitive and R. meliloti most sensitive to low pH. These factors may act either directly on rhizobia or indirectly through their effect on the host plant, which commonly is the more sensitive of the symbiotic partners.

The requirement for calcium is definite but low (approximately 10 μM) in simple media. Nevertheless it has been demonstrated that calcium can limit nodulation of T. subterraneum by restricting growth of rhizobia in the rhizosphere (Loneragan and Dowling 1958).

The tolerance of rhizobia so far studied to manganese is large, so it is unlikely to limit their growth and survival in acid soils.

Recent studies have shown rhizobia to be sensitive to levels of aluminium (50 μM) which may be encountered in acid soils. Tolerance of low pH did not necessarily confer tolerance of aluminium; 40% of those tolerant of pH 4.5 were sensitive. Aluminium appears to be more commonly a severe stress than low pH (Keyser and Munns 1979). The tolerances of strains of rhizobia to the acid soil complex still await confirmation in field trials.

Movement of Rhizobia in Soil

An understanding of the movement of micro-organisms in soil is of particular significance to ecological studies of introduced species. It is especially relevant to studies of Rhizobium spp., as their spatial distribution is a major factor determining the onset and pattern of nodulation on legume roots. Vertical movement of bacteria in soil depends on pore size and distribution, the type and amount of colloidal fraction, its pH and the size of the bacteria, and their extracellular polysaccharide. R. trifolii applied to seedling roots did not move through the profile of dry sandy soil unless flushed by water (Worral and Roughley 1976); a growing root had no effect. In saturated soil, rhizobia moved rapidly, or when unsaturated soil was watered and allowed to drain, rhizobia also moved rapidly down the profile.

The ecological implications of these findings are that rhizobia appear to require saturated soils to move actively down the profile, otherwise they rely on free water movement; they are not transported by growing roots. Therefore when rhizobia are introduced into dry soil by seed inoculation they are likely to remain at the depth of seeding and be subject to desiccation and wide fluctuations in temperature unless distributed by rain or irrigation. Rhizobia injected deeper into the soil by spraying suspensions of the cells may be better able to survive adverse conditions.

Root Infection

Rhizobia may enter the root via one of two pathways, namely, invagination of the root hair and subsequent infection thread formation or by direct invasion of the root at the point of emergence of lateral roots. The mode of entry is under host control so, e.g., strain CB756 invades Arachis hypogea directly and Macroptillium atropurpureum by infection threads.

The series of steps which lead to invasion of the root by rhizobia and the development of the infection has been reviewed in detail by Bauer (1981). This review includes recent studies of the recognition process between rhizobia and the root surface and discusses the possible mechanism of cell-to-cell binding.

Before infection, numbers of rhizobia increase in the rhizosphere of the host seedling which appears to exert some selection pressure. The first observable host response is a bacterial induced marked curling of the root hairs. Several

hypotheses have been proposed to account for the recognition process. The most recent suggests involvement of plant lectins, which provide a feasible explanation of specificity. However, this reaction may not be general (Law and Strijdom 1977). The evidence is nevertheless substantial enough to provide a working hypothesis and to test further the interaction between the bacterial cell surface and plant-produced lectins.

Rhizobia penetrate the curled root hair by localized digestion of the root hair wall (Callaham and Torrey 1981). New wall material is formed, surrounding the bacteria as they penetrate the hair, forming an infection thread. Thus, the bacteria remain extracellular within the root hair. Either the tightly curled root-hair tip, or a flock of bacteria surrounding the pore, prevents widespread bacterial invasion. Nevertheless, more than one strain of rhizobia can invade a nodule. Many threads in clover root hairs abort before reaching the root. Infections are not distributed at random along the roots but are at first restricted to zones around a single infection. Later, infections spread out from these zones, reducing their demarcation.

The early stages of infection in particular are affected by environmental conditions. The lower limit of temperature for infection is dependent on the host plant but may be modified by the Rhizobium strain. Temperatures above the optimum for N_2-fixation in subterraneum clover (22°C) stimulate root infection. Infection-thread formation is very sensitive to low pH, more so than nodule development. All stages of infection including thread growth are sensitive to nitrate—root-hair curling is reduced, fewer infections form, more abort and appear disorganised.

Moisture stress affected the number and distribution of infected root hairs of T. subterraneum even though the population of rhizobia in the rhizosphere was unaffected. At low soil moisture, root hairs were abnormally short, swollen, and resistant to infection (Worrall and Roughley 1976).

After penetrating the root hair, the infection thread passes through and between cortical cells, branching frequently. Cells in the inner cortex are stimulated to divide in advance of the infection threads, usually opposite protoxylem points. Nodule initiation therefore appears to involve hormones of both plant and bacterial origin.

Infection of Arachis and Stylosanthes spp. is initially an intercellular process restricted to lateral root axils. The separation of epidermal cells at these sites is probably helped by the emergent root and its root hairs and also by the enlargement of the basal cell. Infection sites have been observed only where these cells were present. The penetration of the young nodule cells and root-hair bases involves striking changes in wall structure not unlike those in nodules infected through infection threads but, once the many original penetrations have been achieved, the bacteria cease to multiply in the intracellular spaces, and further colonization of the nodule by bacteria is intracellular by host cell division (Chandler 1978, Chandler et al. 1982).

The direct mode of infection may explain the less specific nature of the Rhizobium requirements of Stylosanthes and Arachis (Dart 1977). Nevertheless Stylosanthes do demonstrate a degree of specificity (Date and Norris 1979). Invasion through a gap in the host epidermis would remove that part of specificity due to chemical binding and could lead to a high incidence of infection by more than one strain of Rhizobium at each infection site. This relative lack of specificity may militate against nodulation by introduced strains in competition with soil rhizobia.

Rhizobium Genetics—Its Role in the Symbiosis

Natural Variation

Mutation resulting in colonial and symbiotic deficient variants of strains of rhizobia is well documented (e.g., Denarie et al. 1976). Experience gained in legume inoculant quality control in Australia indicates this to be a common and widespread phenomenon in all species and within the cowpea miscellany (Roughley 1976). Its implications for agricultural exploitation of rhizobia are obvious; less widely recognised are the dangers arising from the possibility of changes following the introduction of a strain into the soil. Experience has shown that some strains are more stable than others thus indicating the need to assess this characteristic when selecting or constructing strains for agricultural use.

Genetic Manipulation of Rhizobia

Although characterization of Rhizobium genes has not kept pace with some of the non-symbiotic nitrogen-fixing micro-organisms, remarkable progress has been made in the last decade. Two general approaches have been made. One has been aimed at producing highly effective, competitive strains directly, while the other seeks to produce a series of deficient mutants to better understand the steps and genes involved in establishing an effective symbiosis. The direct approach has yet to prove itself.

The production of deficient mutants by gene manipulation and the resulting interspecific transfer of symbiotic genes provide further evidence of the direct role of the bacterium in host specificity. There is mounting evidence that these genes are located on plasmids which under some circumstances may be heat-cured, rendering the strain Nod^-. Whether this occurs in nature is not known. Plasmids may be relatively unstable, and the loss of one carrying symbiotic genes would cause a failure at one or more of the stages necessary to establish a fully effective symbiosis. This is likely to be a major cause of the phenotypic variants Fix^- or Nod^- noted above in fast-growing strains. In the slow-growing strains there does not appear to be the equivalent plasmid carrying symbiotic genes (Rolfe and Shine 1984). Nevertheless these rhizobia are still subject to producing Fix^- mutants.

Evidence for the location of symbiotic genes on plasmids is based on experiments which show that cultures with a deficient plasmid profile lose their

ability to form nodules. This loss of nodulating capability may be reversed by transferring self-transmissible symbiotic plasmids to these strains.

Nitrogenase structural genes have been mapped on Rhizobium plasmids including transmissible symbiotic plasmids. Some of the other genes located on plasmids include Roa^+ (root adhesion), Hac^+ (hair curling factor), the synthesis of rhizobial exopolysaccharides, Hup^+ (hydrogenase production), Pig^+ (pigment production) and bacterium production (Rolfe and Shine 1984). The nodulation region of an R. trifolii strain has been cloned carrying genetic determinants for nodule initiation, development and host specificity. These experiments offer exciting prospects for strain construction in the future.

Scope for the Improvement of Rhizobium Strains

Agronomically desirable strains of rhizobia should have the ability to nodulate their host promptly and fix nitrogen over a wide range of environmental conditions and be able to compete with naturalised rhizobia in the soil.

Historically, there has been much emphasis on the role of the bacterium as a determinant of the success, or otherwise, of a symbiosis. Terms such as 'effectiveness' and 'ineffectiveness' in fixing N have often been inferred to be immutable, but it is now generally understood that these terms should be related to specific conditions. The genetic heterogeneity among wild strains of Rhizobium has made selection from such populations the most profitable first step in the improvement of nitrogen fixation. For example, improved selections of R. trifolii have been made for tolerance of low soil temperatures (Ek-Jander and Fahraeus 1971), of cowpea rhizobia for tolerance of high soil temperatures (Day et al. 1978) and of R. trifolii for greater competitive ability (Roughley et al. 1976). Nevertheless, these desirable strains must still be established in sufficient numbers to remain a substantial, stable, naturalised component of the population of Rhizobium in the soil.

Improved strains are sought from within a large population of isolates selected from a particular host or environment. It remains a lottery and is extremely time-consuming and costly. Little is still understood of the basis of a desirable strain, so that selection is based on phenotypic expression in glasshouse and field trials. Until recently there was no opportunity to construct a strain, but rather all desirable attributes must already have been combined naturally.

The research for more energy-efficient strains can now be made based on the physiology and genetics of the rhizobia. Hydrogen is a by-product of nitrogen fixation. Some strains of rhizobia are able to recycle this hydrogen using their uptake hydrogenase, although the expression of this gene (Hup^+) can be modified by the host (Gibson et al. 1981). Considerable attention is being paid to this pathway, and more information is required before the potential savings can be estimated, but these could be of the order of 5% (Schubert and Ryle 1980). Other strains have been shown by Witty et al. (1984) to have a lower respiratory cost (moles CO_2/mole ethylene reduced from acetylene). They showed that the efficiency of strains of R. leguminosarum ranged from 2.25 to 4.52.

The now well described techniques of gene transfer (Rolfe and Shine 1984) allow the possibility of genetic strain construction. In its most attractive form it will allow well tested strains to be conserved but at the same time for a particular function to be modified to extend the strains' usefulness.

Currently the host range of fast-growing strains of rhizobia may be extended by transfer of symbiotic plasmids; however, the constructed strains generally fail to fix nitrogen with their new hosts. Exceptions include transfers between R. trifolii and R. leguminosarum and between R. phaseoli and R. leguminosarum. Such possibilities at present appear restricted to fast-growing rhizobia, as the symbiotic information for slow-growing strains appears to be chromosomal.

This field is advancing so rapidly that the future is hard to predict; it is, however, easy to be optimistic. Nevertheless it must be remembered that success in establishing a strain depends principally on its ability to compete with rhizobia already established in the soil and on the number of cells introduced. Strains vary in their competitive ability and effectiveness, and these characters are not necessarily linked nor is their genetic base well understood. This limits our ability to capitalise on highly effective strains whether naturally selected or genetically constructed. Understanding the basis of competition and exploiting this in strain construction will therefore be of major importance.

Utilising Improved Strains of Rhizobia

Expectations for results following inoculation depend largely on the number and effectiveness of the existing population in soils. At a Rhizobium-free site, inoculation allows the host to survive long enough for a mixed population of rhizobia to establish. From this population the host may select the most suitable strains.

At a competitive site it is hoped the more effective strains will not only compete well with naturalised strains in forming nodules in the first year but also will persist in sufficient numbers and remain stable to perform well in succeeding years. The competitive ability and persistence of strains are desirable characters for selection of strains in commercial legume inoculants. However, results for such selected strains indicate that expectations from inoculation in competitive sites require re-assessing. R. trifolii strain WU95 was selected for its competitiveness but failed to persist in sufficient numbers in competitive sites after two seasons in New South Wales (Roughley et al. 1976). Even where plots were initially free of rhizobia they were invaded by other strains of rhizobia which formed a significant proportion of the nodules in the third season. At such sites, with existing technology, a strain of R. trifolii may at best be expected to form most of the nodules in the first

season. Inoculation of pasture seed at such sites has few if any long-term benefits.

It is safe to predict that increased demands will be made by the agriculturists for larger numbers of rhizobia to be applied per seed in inocula as harsher environments are sown with legumes or established areas providing competitive situations are re-sown. Also the proportion of the seed which will be pre-inoculated, often well before sale to the farmer, will increase. Both these situations must be met either by increasing the number of rhizobia in legume inoculants or improving their survival on seed. It is general experience that numbers of rhizobia in peat inoculants are regularly in the range 1-5 x 10^9 g^{-1}; a tantalising few reach 10^{10} g^{-1}. Nevertheless prospects for increasing inoculant quality significantly are not good, but the number of rhizobia which survive on seed can be much improved by seed pelleting and use of adhesives. Further work on these aspects together with improved management techniques seem to offer the greatest opportunity to meet the challenges posed above.

Future Research Needs

Crucial to improving nitrogen fixation inputs via the rhizobia is the need to define the biological basis for competition between strains for nodule sites. The confusing evidence in the literature, based on many studies, suggests that the use of deletion mutants of rhizobia may offer a better method with which to attack this problem.

There then would follow the possibility of constructing more competitive strains which would then make it feasible to use strains selected or constructed for particular purposes. These may include strains to assist in overcoming environmental constraints on nodule initiation or strains more effective in nitrogen fixation.

Concurrent with this approach, the selectivity of the host should be exploited. Host specificity varies between cultivars of the one species so that host/strain matching may be developed to reduce competition from naturalised rhizobia in the soil.

The chances of introducing selected rhizobia may be further enhanced by developing inoculation techniques to ameliorate those factors responsible for death of rhizobia in inoculated seed.

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Discussion

Stern: The point made about competition seems important. Can you elaborate on this point in the management of Rhizobia and the host?

Roughley: The topic is complex. The host may play a most important part in this by selecting more effective strains. Unfortunately, this is not universally so and not well enough understood to exploit. There appears to be some hope from breeding as some plants are less promiscuous than others and may be matched to a group of strains. As an example, the cultivar of sub. clover, 'Woogenellup', is less promiscuous than, e.g., 'Mt. Barker'. The biology of competition is not understood, which makes strain construction difficult; but Dr. Rolfe at ANU has some mutants of Rhizobia which have aided in understanding the role of Rhizobia and suggests that successful strain construction for increased competitive ability will result. It clearly involves a suite of genes.

Sheath: Work at Whatawhata suggests that the initial strain used for inoculation was ineffective but that within a year there was natural selection of a more competitive strain. Is this your experience?

Roughley: Yes, this can occur as a result of host selection but unfortunately the opposite result is also common. Until competition from indigenous strains is better understood, we need to reassess the value of inoculation. At present we can only expect to form a high proportion of the nodules with the inoculant strain at competitive sites in the first year only. This clearly limits the agricultural exploitation of strains selected for tolerance to particular constraints and effectiveness in nitrogen fixation.

Role of the Legume in the Legume-*Rhizobium* Symbiosis

G.H. Heichel and Laura S. Brophy[1]

Abstract

Genetically controlled traits of the host and of *Rhizobium* are important in determining the dinitrogen fixation capability of the symbiosis. This review considers some traits of the host legume important to establishment of the symbiosis, accumulation of nitrogen, and release of nitrogen. The mechanisms of plant-rhizobial specificity and root infection are becoming known, but dominant roles in these processes cannot yet be assigned to either symbiont. Root system morphology is genetically controlled and has been successfully modified to enhance nodulation. Earliness of nodulation is also under host control, but this trait has not yet proved useful in plant improvement. Nodule mass has been enhanced to improve dinitrogen fixation capability in several species. Host genes that condition the effectiveness of established nodules are known in many species. Rate of nitrogenase activity, measured over short intervals of the host life cycle, is under host genetic control through association with nodule mass and number. Activity of nitrogenase is closely associated with that of other nodule enzymes for nitrogen and carbon assimilation. There is meager evidence that nodule longevity or duration of activity is under host control. The interaction of longevity with environment and management has inhibited its usefulness in selection for increased dinitrogen fixation. There is no evidence that host variation in photosynthetic CO_2 assimilation limits dinitrogen fixation. However, selection for reduced nonphotosynthetic CO_2 assimilation in nodules of alfalfa reduced dinitrogen fixation. Genetic variation for storage of nitrogen in shoots and in roots of alfalfa is known. Insufficient understanding of factors important to nitrogen release from legumes precludes their use in selection programs.

Introduction

The forage legume-*Rhizobium* partnership may provide 100% of the nitrogen needs of the plant from the atmosphere. Two genomes interact in symbiosis, and characteristics of both are important in determining the nitrogen content of the forage legume. The complementary roles of both organisms are only beginning to be exploited in crop germplasm improvement, this since the advent of breeding programs designed to manipulate host traits to improve dinitrogen fixation capability. In one program, Viands et al. (1981) found that 43% of the experimental variation in nitrogenase activity per alfalfa (*Medicago sativa* L.) plant was attributable to plant traits measured during two cycles of recurrent selection. The remaining 57% of experimental variation was unexplained and was thought to be largely attributable to host-*Rhizobium* interactions, since the inoculum was a mixture of rhizobial strains instead of a single strain. In another program (Jessen 1984), nodule mass of alfalfa explained 59% of the experimental variation in nitrogenase activity per plant.

The meager experimental evidence now available suggests that characteristics of both partners contribute to the short-term nitrogenase activity of the nodulated plant, but that there may be facets of the symbiosis in which either the plant or the *Rhizobium* exerts the dominant role. This paper will briefly survey our knowledge of some of the plant traits that might contribute to the success of the symbiosis. They will be considered under three broad phases of legume ontogeny corresponding to establishment of the symbiosis, nitrogen accumulation, and nitrogen release, with emphasis on identifying characteristics amenable to selection or manipulation in forage legume breeding programs.

Establishment of the Symbiosis

Formation of nodules involves synchronization of plant and bacterial development at a number of stages, beginning with seed germination. Following seed germination, root exudates such as amino acids may preferentially stimulate the multiplication of bacteria in the rhizosphere. Upon contact of legume root by root-nodule bacteria, modifications of seedling root hairs may occur. Branching, moderate curling, and marked curling (360°) of root hairs occur through complex but poorly understood mechanisms that nevertheless signal close contact between host cells and an infective microsymbiont. The mechanism of root hair curling involves differential root hair wall synthesis, perhaps mediated in part by growth hormones. These processes have been reviewed in detail by Vance (1983).

Specificity for Rhizobial Strain

Specific contact between elicitor compound(s) on the surface of the bacterium and receptor compound(s) on the surface of the root hair are required for mutual recognition (Vance 1983). Enzymes of carbohydrate synthesis on the surface of bacteria may be the elicitors of recognition between the root nodule bacterium and the plant, while sugar-binding proteins called lectins on or in root hair cell walls may be receptors for recognition (Vance 1983). Initial attachment of the bacterium to the root surface is thought to occur with lectin from the root cell binding together structurally similar complex sugars on the root hair and the bacterial capsule. An alternate hypothesis suggests that the oligosaccharides in the mucilaginous capsule of the bacterium regulate specificity and binding. At this

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point, we cannot speculate which partner has the greater role in the recognition process.

Root System Phenotype

The phenotype of the legume root system, principally exemplified by its morphology, strongly influences the quantity and total mass of nodules formed. Nodules form sooner and more abundantly on seedlings of subterranean clover (Trifolium subterraneum L.) having rapidly rather than slowly elongating primary roots (Gibson 1967). Root systems of red clover (Trifolium pratense L.) and subterranean clover with abundant lateral root growth form more nodules than those with sparse lateral roots (Nutman 1948, 1967).

These early observations on the importance of root system phenotype in dinitrogen fixation have been recently confirmed and exploited in breeding programs on forage legumes. Selection for abundance of lateral or fibrous roots has been associated with increased nodulation and increased nitrogenase activity per plant in crimson clover (Trifolium incarnatum L.) (Smith et al. 1982) and alfalfa (Duhigg et al. 1978, Viands et al. 1981). Modification of root phenotype by increasing the number of lateral or fibrous roots, and therefore the number of sites for nodulation, is one approach to improving dinitrogen fixation capability.

Onset of Nodulation

A legume host exerts some control over the rate of initiation of nodules, even when the root is confronted with a highly competitive and infective rhizobial strain. Some of this control may be related to rate of root elongation (Gibson 1967) and to interspecies variation in the length of time that root hairs remain susceptible to infection (Bhuvaneswari et al. 1981). There are no published observations on intraspecies variation in duration of root hair susceptibility to infection.

The most thorough work on host effects on onset of nodulation has been done with subterranean clover. Gibson (1967) observed a range of 1.6 to 2.6 days among four cultivars in the time to formation of first visible nodule. Nutman (1967) observed a range of 2.8 to 5.8 days among 13 varieties in days to first visible nodule. Although days to onset of nodulation varied significantly with variety, it was unresponsive to ploidy level and was polygenetically inherited. Similar times to onset of nodulation have been found among varieties within a single species of Stylosanthes, and among species within a genus (Graham and Hubbell 1974).

Onset of nodulation in forage legumes is clearly under genetic control. However, nodule initiation is also strongly affected by root temperature, nitrate concentration in the soil solution, soil solution pH, and rhizobial strain. The environmental effects on nodulation, the relatively small variation within a species for onset of nodulation, and the potentially minor change in duration of nodule activity that might be achieved by selection for this character suggest that selection for time of nodulation would be a minor value in a program to improve legume dinitrogen fixation.

Nodule Development

Although root hair infection is thought to occur through enzymatic dissolution or stretching of the cell wall by the bacterium (Vance 1983), several types of evidence illustrate host control over the subsequent development and functionality of the nodule. Bhuvaneswari et al. (1981) observed differences among forage legume species in the portion of the root that was susceptible to infection and in the duration of susceptibility to infection. Similar mechanisms may be responsible for the interspecies variation in earliness of nodulation discussed above.

Host control of functionality in nodules formed by effective rhizobial strains has long been known (e.g., Gibson 1962) and is becoming increasingly well documented (Hardarson and Jones 1979, Hardarson et al. 1982). Nodulation in some alfalfa germplasms is apparently mediated by one of the two known genetic mechanisms of resistance to the bacterial wilt pathogen, Corynebacterium insidiosum (McCull) H.L. Jens (Viands et al. 1980). Recessive genes in red clover (Nutman 1954), Lotus spp. (Gershon 1961), subterranean clover (Gibson 1964), and alfalfa (Viands et al. 1979, Peterson and Barnes 1981) condition the formation of ineffective nodules or entirely prevent nodulation by bacteria that effectively nodulate other genotypes of the host. Ultrastructural changes accompanying the action of these recessive host genes have been investigated (Vance et al. 1980). Knowledge of the genetic control of nodule development in forage legumes will be important to the future development of germplasm, allowing controlled nodulation by specific rhizobial strains.

Nodule Mass

Nodule mass per plant is the product of mean nodule number and mean mass per nodule. Owing to the small size of nodules, nodule mass per plant or nodule volume are infrequently measured, and the individual components are measured even more rarely. Nodule mass and number per plant are inversely correlated in some species (Nutman 1967), while the converse holds for others. Despite this interspecies variation, nodule mass (or volume) per plant is often found to be closely associated with short-term measurements of dinitrogen fixation.

Recorded values of nodule mass per plant range at least eightfold among legume species and are correlated with short-term rates of nitrogenase activity (Graham and Chatel 1983). Owing to differences among species in the specific nitrogenase activity of the nodules and the duration of nodule activity, mass of nodules per plant may seldom be a reliable means of estimating seasonal dinitrogen fixation capability.

Variation among cultivars or strains within a legume species for nodule mass has often been observed (Nutman 1967, Seetin and Barnes 1977, Smith et al. 1982) and shown to be amenable to selection in plant-breeding programs. Two generations of selection increased nodule mass per plant in white clover (Trifolium repens) (Mytton and Jones 1971) and alfalfa (Viands et al. 1981), and short-term

rates of nitrogenase activity were highly correlated to nodule mass (Seetin and Barnes 1977, Viands et al. 1981, Smith et al. 1982). Although nodule mass is a plant trait easily modified by host selection, its ultimate value depends upon being combined with rapid rates and a long duration of nodule activity.

Accumulation of Nitrogen

The accumulation of atmospheric dinitrogen by legumes varies with the activity of the nodule system, the duration of symbiotic activity, the carbon nutrition of the legume, the synthesis and partitioning of compounds for transport of fixed nitrogen, and the storage of nitrogen within various organs. Interspecies variation is known for all of these characteristics, but intraspecies variation is evident only for a few.

Nitrogenase Activity: Rate

Variation among legume species for rate of nitrogenase activity measured over periods of minutes or hours is well documented (Graham and Chatel 1983). However, the variation of nodule activity among genotypes within a species is often as great as variation among species (Heichel 1985). Demonstration of genetic variability within legume species for rate of nitrogenase activity per plant, and that nitrogenase activity is a heritable trait conditioned by host genes, has recently occurred for white clover (Hardarson and Jones 1979), alfalfa (Duhigg et al. 1978, Viands et al. 1981), crimson clover (Smith et al. 1982), and red clover (Boller 1983). The control of this trait is largely vested in nodule mass and number per plant, there being no convincing evidence of intraspecies variation in nitrogenase activity per nodule mass except that conditioned by host genes for ineffective nodulation. The intraspecies variation in short-term nitrogenase activity is often associated with the activity of other nodule enzymes, specifically those for assimilation of ammonia (Groat et al. 1985) and carbon dioxide (Jessen 1984).

Nitrogenase activity per plant is strongly influenced by the environment, often making results for a genotype obtained under one set of assay conditions inapplicable to another (Heichel et al. 1981). Despite this sensitivity to environment, the interdependence of nodule mass and nitrogenase activity per plant has led to relatively easy manipulation of the latter trait in forage legume breeding programs.

Nitrogenase Activity: Duration

The quantity of fixed nitrogen available to the host plant clearly depends on the duration of nodule function as well as on the mass and activity of the nodule tissue. The duration of nodule function varies with plant species and their management, with nodule morphology, strain of microsymbiont, environment, and edaphic conditions. Sutton (1983) thoroughly reviewed these factors.

The elongate, cylindrically shaped, frequently branched nodules of alfalfa and clover that have persistent infection threads and long-lived apical meristems function longer before senescence than the spherically shaped nodules like those of birdsfoot trefoil (*Lotus corniculatus* L.), which have short-lived infection threads and transient apical meristems (Vance et al. 1982). Alfalfa nodules undergo partial senescence at the base of the nodule following herbage removal, and resumption of nodule activity coincides with reactivation of the apical meristem, renewed infection of nodule cortical cells, and regrowth of herbage (Vance et al. 1978, Cralle and Heichel 1981). Similarly, Butler et al. (1959) observed an accelerated loss of nodules from bigflower trefoil (*L. pedunculatus* L.) following repeated herbage removal, but not from white or red clovers. Alfalfa nodules can also overwinter in frozen soil and exhibit renewed activity the following spring (C.P. Vance and G.H. Heichel, unpublished data).

In contrast, nodules of birdsfoot trefoil suffer complete senescence following herbage removal, and a new nodule population apparently develops following regrowth of the shoots. The nodule growth patterns of these contrasting species also respond similarly to the stress of excess nitrate and probably to other stresses as well.

Since longevity of nodules is closely related to growth habit of the host, intraspecies differences in duration of nodule activity are more easily observed in herbaceous annuals such as soybean, which undergo maturation and senescence, than in perennial herbaceous species such as alfalfa, trefoil, or some clovers. However, substantial variation in duration of nodule activity has been observed within the genus *Desmodium* (Whiteman 1970). Differences among species in nodule longevity have been correlated to the activity of nodule proteolytic enzymes (Vance et al. 1985). An alternate explanation is that plant inhibitors of *Rhizobium* cell wall synthesis are responsible for bacteroid viability within nodules (Sutton and Paterson 1983). Despite the gross differences in duration of nodule activity that have been observed, there is insufficient understanding of intraspecies factors governing nodule longevity for this to be a trait amenable to selection in a forage legume breeding program.

Carbon Nutrition

The similarity of growth rates and dinitrogen fixation rates often observed for forage legumes (Heichel et al. 1981) illustrates the interdependence of carbon nutrition and nitrogen assimilation on a seasonal or life-cycle basis. The initial observations on clover and alfalfa (Wilson et al. 1933) of the association between nitrogen accumulation and photosynthetic capacity have been thoroughly confirmed on perennial forage legumes as well as on annual legumes by source-sink manipulations, carbon dioxide enrichment, and variable photosynthetic photon flux densities (Heichel and Vance 1983). On a short-term basis of measurement, plants with higher rates of nitrogenase activity per plant are usually larger or faster growing than those with low rates of nitrogenase activity (Viands et al. 1981, Smith et al. 1982). However, large, vigorously growing plants need not fix large amounts of dinitrogen if they are being grown under conditions where nitrate is plentiful.

On a seasonal basis, differences in forage or total phytomass productivity of alfalfa, and between alfalfa and birdsfoot trefoil are directly proportional to content of nitrogen fixed by symbiosis (Heichel et al. 1984). Productive alfalfa clones generally fixed more nitrogen than did less productive ones (Heichel et al. 1985), an illustration of the principle that any alteration of photosynthetic rate that is integrated over a sufficiently long period will be reflected in nitrogen accumulation from symbiosis (Sheehy et al. 1980). Owing to the absence of legumes having the C_4-dicarboxylic acid pathway of photosynthetic carbon assimilation, no inferences can be drawn on the role of C_3 vs. C_4 pathway in dinitrogen fixation. Similarly, there is no definitive evidence that varietal differences in rate of leaf CO_2 assimilation are related to differences in the dinitrogen fixation capability of varieties.

There is evidence that non-photosynthetic CO_2 fixation by phosphoenolpyruvate carboxylase (PEPC) of legume nodules may contribute to the carbon economy of certain legumes (Christeller et al. 1977, Maxwell et al. 1984). The carbon assimilated by nodule CO_2 fixation is incorporated primarily into amides in species like alfalfa that export fixed nitrogen from nodules as amides and amino acids, and primarily into organic acids in species like soybean (Glycine max (L.) Merr) that export fixed nitrogen from nodules as ureides (Maxwell et al. 1984). The rate of PEPC activity in alfalfa shows substantial genetic variability, and germplasm bred for a diminished PEPC capability also fixed less dinitrogen (Jessen 1984). While a certain activity of nodule PEPC appears essential for normal dinitrogen fixation, evidence that dinitrogen fixation among or within species is constrained by any factor related to nodule carbon metabolism is lacking.

Nodule Export Compounds

Legume species can be classified according to the type of metabolites containing fixed nitrogen that are exported from the nodule through the xylem (Sprent 1980). Species of the tribe Phaseolae principally export the ureides allantoin and allantoic acid, while those in the Vicieae and Trifolieae principally export amides and amino acids. Classification by legume use or management regimen is ineffectual, as legumes used for grain in temperate regions are often used as forages (browse or pasture) in tropical regions, and conversely. Variation among species in type of nodule export product may have a basis in evolution, adaptation, or efficiency of metabolism, but no relation to dinitrogen fixation capability is known. Similarly, no intraspecies variation in nodule export product except that caused by nitrate fertilization has been reported.

Nitrogen Storage

Nitrogenous compounds accumulate within organs of forage legumes and are either sequestered until the organs are harvested or degrade, or are mobilized after harvest to sustain growth of new tissue. Nitrogen storage as protein in herbage is an important determinant of forage quality. Nitrogen stored in subterranean organs and crop residues becomes available to companion or succeeding crops after phytomass degradation. Variation in crude protein concentration (Heinrichs and Troelsen 1965, Heinrichs et al. 1969) and fraction I protein concentration (Miltimore et al. 1974) has been reported for alfalfa varieties or strains, and a screening program recently identified differences in shoot crude protein of genotypes from two nonwinterdormant alfalfa germplasms (Phillips et al. 1982).

Improvement of the storage capability of legume roots and crowns is one approach to increasing the residual nitrogen content of these organs for use as green manures. Two cycles of recurrent phenotypic selection for concentration of nitrogen in root tissue increased whole plant nitrogen concentration 4% to 14% in two of three nonwinterdormant alfalfa germplasms (Heichel and Barnes 1984). Nitrogen fixation capability was also increased slightly by selection.

In companion experiments, two cycles of selection for larger crowns and roots in nonwinterdormant alfalfa showed encouraging progress in two of three germplasms (Heichel and Barnes 1984). The root and crown mass of the second-cycle nonwinterdormant entries was greater than that of the winterdormant controls, which supported the idea that the input of nitrogenous residues to the soil might be increased by such selection. Thus, potential exists within alfalfa for development of germplasm with increased nitrogen storage capability for use as a source of high-quality forage, or as an improved nitrogen source in rotational cropping systems.

Release of Nitrogen

Nitrogen release from forage legumes is important in animal nutrition and in the use of legumes as nitrogen sources in cropping systems. The plant factors governing the ease of degradation of legume tissues in the rumen and the release of nitrogen for assimilation are beyond the scope of this article. We will instead concentrate on factors governing release of nitrogen from living and from senescing plants.

Release by Living Plants

Nitrogenous compounds are released from both shoots and roots of legumes. Gaseous ammonia is evolved and absorbed by legumes and nonlegumes (Denmead et al. 1976, Lemon and Van Houtte 1980), but the factors governing this phenomenon are poorly understood. Differences among species that are unconfounded with culture method and stage of ontogeny are unknown, as is the significance of the phenomenon to the crop's nitrogen economy.

Nitrogenous root exudates from legumes have been identified and quantified by laboratory and greenhouse experiments. By extracting the culture medium after plant removal, Boulter et al. (1966) found up to 1,270 g amino acids/g root dry weight for peas (Pisum sativum L.) grown in nutrient solution, and up to 4,570 g amino acids/g root dry weight for those grown in sterile quartz sand. Homoserine, aspartic acid, and glutamic acid were

the most prevalent amino acids. Ammonia was also found in the medium at up to 1,500 mg/g root dry weight. Richter et al. (1968) found release of 0.2 to 0.5 moles total amino acids per 72 alfalfa plants per week in sterile sand culture. Alanine, glycine, threonine, serine, ornithine, and aspartate were most abundant in the exudates. Proteins, peptides, and nucleic acids have also been identified in root exudates (Fries and Forsman 1951, Juo and Stotzky 1969, 1970, Vancura and Hanzlikova 1972). Nitrogenous compounds released from roots initially nourish the soil microflora, but may be recovered by the source plant or by neighboring plants after sufficient mineralization of microbial biomass.

Nitrogen Transfer to Companion Plants

Transfer of nitrogen from forage legumes to neighboring grasses has been observed in both controlled and field environments. Bland (1967) grew grass and white clover in plots with either segregated or integrated root systems and calculated a transfer of about 34 kg N/ha yr among species in integrated stands during the third year. Cowling and Lockyer (1967) calculated transfer of 26 kg N/ha from white clover to perennial ryegrass (Lolium perenne L.) and 52 kg N/ha from clover to orchardgrass (Dactylis glomerata L.) in swards cut four to five times annually for hay. Johansen and Kerridge (1979) measured transfer of 12% to 17% of the legume nitrogen fixed by Macroptilium atropurpureum L., Glycine wightii L., Desmodium intortum L., and Lotononis bainesii L. to companion grasses. Under a regime of periodic mowings over 3 years in which all clippings were removed, cumulative transfer of legume nitrogen to orchardgrass was 20% for subterranean clover, 6% for white clover, and 3% for alfalfa (Simpson 1976). The differences among species were apparently attributable to senescence of nodules, roots, and stolons of clovers after harvest. Comparatively little root (Hodgkinson 1969) or nodule (Vance et al. 1979, Cralle and Heichel 1981) turnover occurred after alfalfa harvest. Although quantitative data on nodule biomass in the field are rare, Heichel et al. (1983) calculated that a typical alfalfa stand in the upper midwestern United States might contain no more than 5 kg N/ha in root nodules. This is scarcely sufficient to be a significant factor in the nitrogen economy of neighboring grasses.

Use of nitrogen-15 isotope dilution methodology is becoming increasingly important in quantitating nitrogen transfer from legumes to neighboring grasses. Haystead and Marriott (1978) observed that pot-grown ryegrass received 27% of its nitrogen from associated white clover over a 17-week period, while field-grown ryegrass on the same soil obtained less than 6% of its nitrogen from the associated white clover. Subsequently, Haystead and Marriott (1979) measured that ryegrass obtained 12% of its nitrogen from associated white clover, with transfer occurring only at the fourth harvest of a 105-day season. Broadbent et al. (1982) found that ryegrass grown in the field obtained up to 80% of its nitrogen from associated ladino clover (T. repens L.), but no transfer was observed in the glasshouse. Contrasting results on nitrogen transfer between field and glasshouse investigations are common.

In all such nitrogen transfer experiments, the method and mechanism of transfer are unclear. Although direct excretion or degradation of root and nodule tissue are the usual explanations (Mulder et al. 1977), a budget to account for nitrogen transfer from various sources has not been attempted. Despite the emphasis on root and nodule degradation, stolon decay may be important in some forage legumes, loss of leaves to pests or pathogens in others, or death of individuals on the sward. Furthermore, legume species are known to differ in their rate of degradation in soil, and in recovery of nitrogen by a subsequent crop (see G.H. Heichel, "Nitrogen Recovery by Crops That Follow Legumes," later in these proceedings). At this stage, we are only learning of those management or environmental factors conducive to legume-grass nitrogen transfer among different legume species. Development of cultivars within species with attributes enhancing their use as nitrogen sources for companion plants has not proven successful.

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Discussion

Barry: You selected for root-hair development in lucerne. Was there an effect on improved phosphate foraging with the extra root hairs?

Heichel: No data are available on nutrition effects, but improvement in frost-heaving resistance was noticed.

Marten: How soon will the alfalfa with increased N storage and fixation be released?

Heichel: The ineffectively nodulated mutant material is being released as a germplasm. The other selections (for N_2 storage and for better N_2 fixation) will be released in 2-4 years.

Ball: Harvest Index is an important index for transfer of N_2 in legumes in New Zealand. The less of a plant that is harvested, the less is available (via the animal) for recycling back into the soil.

Bray: The possibility of selecting for preference for rhizobial strains seems potentially dangerous, for, unless the specific strains can compete effectively with native strains, then one may end up with little or no effective nodulation.

Heichel: This danger is a possibility; however, we are discussing a heterogenous crop with a range of effectiveness of nodulation. It is possible to rogue out non-effective nodulators and hence improve the remainder. This does narrow the genetic base.

Easton: Which of the various components is the one with the greatest potential for improvement?

Heichel: Breeding for nodule mass and root phenotype are the obvious and most easily manipulated characters. Work with such characters as nodule enzymes is arduous and extremely time-consuming.

Helyar: What do biochemists accept as the limiting steps in the process? Is it energy supply or nitrogen into the nodule or any other factor?

Heichel: There is no single limiting step. Limits tend to be a complex of the interaction between the plant and its environment.

Helyar: As a supplement to that question, can you expect the same yield from lucerne fertilized with N as from an effectively nodulated plant?

Heichel: Experience is that this is extremely varied, hard to reproduce, and varies with location. However, we have been able to add to productivity of space-planted alfalfa by addition of ammonium nitrate after initial crop harvest.

Stern: You made it look easy to shift a genetic base. Is this really so? If it is so easy, it should be possible to quickly overcome the problems of competition.

Heichel: Yes, it is relatively easy. Must be approached as you would a disease situation. Two cycles can be conducted in a year if you have the personnel resource.

Field: Your enhanced nodule enzyme activity did not seem to increase growth. Was this so?

Heichel: That is correct. However, reduced nodule enzyme activity was deleterious to growth.

Sheath: You have tackled the job on the basis of increasing the N supplied to the plant. Have you considered increasing the plant dry matter produced per unit of N fixed? Is there any variation in this?

Heichel: This has not been tested experimentally. There are differences in assimilation rate. It might be worth looking at this aspect in the future. There are very few research groups in the field--that is the problem.

Nitrogen Fixation by the Legume-*Rhizobium* Symbiosis: External Factors Influencing the Symbiosis

J.R. Crush and W.L. Lowther[1]

Abstract

Nitrogen (N) fixation in mixed temperate pastures is controlled by the interaction of legume demand for N in growth and uptake of soil mineral N. Soil mineral N normally increases during pasture development, reducing both N fixation/unit clover grown and the proportion of legumes in the sward. In a similar fashion there are seasonal interactions between legume growth rate and availability of mineral N, which produce characteristic seasonal patterns of N fixation. Nitrogen fertiliser and urine N are regarded as extensions of the soil mineral N pool. Legume growth rates are influenced by climatic and management factors that may also affect soil mineral N supply. Differences in growth rate and seasonality of growth of legume cultivars interact with patterns of mineral N supply. Grazing strategies, the type of stock used, climatic variations, and pasture pests can all have significant effects on legume yield and N fixation.

Introduction

In discussing external factors influencing the legume-*Rhizobium* symbiosis, we have concentrated on temperate pastures of the type common in New Zealand. In these, mineral nutrient deficiencies are corrected by fertiliser application, while acid soil toxicities are ameliorated by liming. Hence we have assumed adequate mineral nutrition, with the exception of nitrogen (N) of the legume.

We have considered external factors affecting the amount of legume in the sward and the efficiency of N fixation.

Soil Mineral Nitrogen

In temperate mixed pastures, availability of soil mineral N is the most important factor influencing the legume-*Rhizobium* symbiosis. Legume N-fixation rates are governed by the difference between the host plant's demand for N for growth and uptake of soil mineral N. Soil mineral N substitutes for dinitrogen fixation and usually controls the botanical composition and yield of companion species. The companion species may have important influences on the amount of legume grown in a mixed sward, e.g., a summer-active grass like tall fescue will depress white clover yields.

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Stage of Pasture Development

The effects of soil mineral N availability on pasture composition and N fixation are well illustrated in the pasture development sequence described by Sears (1960). On N-impoverished soils, legumes dominate the sward once deficiencies of other nutrients are corrected, and annual N fixation by white clover may exceed 500 kg/ha/yr (Sears et al. 1965). As soil mineral N becomes more plentiful, N fluxes through the plant, and animal pools increase with a concomitant reduction in N fixation, especially in urine patches (Ball et al. 1979). The reduction in clover yields caused by grass dominance, and in fixation per unit clover grown, means that N fixation in a high-producing established pasture may be only 100-200 kg/ha/yr (Hoglund et al. 1979, Crush et al. 1983).

Seasonal Influence of Soil Mineral Nitrogen

Seasonal patterns for mineralisation of soil organic N and immobilisation strongly influence short-term legume N fixation rates. In N.Z. pastures, low soil temperatures during winter may reduce N mineralisation and favour immobilisation (Holland and During 1977). Consequently, despite slow growth rates, competition from grasses for scarce mineral N ensures that clovers are heavily dependent on the symbiosis and N fixation/unit clover grown is high. Fixation efficiency declines in spring, and this is considered to reflect improved availability of soil mineral N as soil temperatures increase (see table 1). In summer and early autumn up to 80% of legume N may be derived from the soil (Hoglund and Brock 1982), although this pattern is not universal (Carran 1979). With the onset of autumn rain, the combined effects of leaching, immobilisation, and assimilation of N, and reduced mineralisation rates as soil temperatures decline, result in an increase in fixation efficiency.

Nitrogen Fertiliser

Nitrogen fertiliser provides a short-term boost to the soil mineral N pool with associated effects on growth of legumes and grasses and N fixation. At the typical rate of application for N fertiliser used on pasture in New Zealand (<50 kg N/ha) there are only minor deleterious effects of grass competition on legume yields in lowland pasture, provided the availability of other nutrients is adequate and the defoliation frequency is not too long (Ball and Field 1982). For example, in intensive dairy beef systems near Palmerston North, two applications annually of 50 kg N/ha lowered clover yields from 2.6 to 2.3 t DM/ha/yr. The major influence of low N fertiliser rates on legumes in these well managed, highly productive pastures is to substitute for dinitrogen fixation and reduce fixation/unit clover grown, as shown by a fall in annual N fixation from 100 to 65 kg N/ha and fixation efficiency from 40 to 28 kg N/t legume DM (Crush et al. 1982). In steep, N-deficient hill pasture, application of urea reduced annual N fixation by 0.31 kg N/kg N applied, but more importantly there was a sustained reduction in clover yield (Luscombe and Fletcher 1982). This depression probably resulted from stimulation of the warm-season active *Agrostis capillaris* turf, at the expense of clover.

Table 1 - Effect of three years of nitrogen fertiliser, at three levels, on nitrogen fixation (kg N/ha) and (in brackets) fixation efficiency (kg N/t clover DM). Data from the third year of a trial reported by Ball (1979)

	Nitrogen Levels (kg/ha)		
	0	112	448
Autumn-winter	47 (67)	35 (38)	14 (21)
Winter-spring	103 (81)	77 (85)	27 (61)
Spring-summer	49 (69)	25 (52)	5 (16)
Summer-autumn	65 (42)	28 (25)	7 (9)

Nitrogen fertiliser is rarely, if ever, used on N.Z. pastures at rates exceeding 50 kg N/ha, and experimental rates are generally less than 100 kg N/ha. Even very high rates of N for 3 years did not completely suppress N fixation in grazed swards (table 1, Ball 1979). No longer term data have been located, nor has any on the effects of cessation of N fertiliser.

Urine Patches

Soluble N in sheep and cattle urine patches (about 300 and 600 kg N/ha respectively) rapidly suppresses N fixation by clovers (Ball et. al 1979, Carran et al. 1982a, Ledgard et al. 1982). The effect is more severe and protracted in winter than in spring and may persist for several months. The initial reduction in N fixation results from substitution of mineral N for N fixation (Ledgard et al. 1982). After about 6 weeks, N fixation/unit clover growth is similar in urine patches and control areas; and the subsequent low levels of N fixation/unit area are caused by reduced clover growth.

As 15%-30% of pasture may be affected annually by urine patches in sheep and cattle systems, the aggregation of herbage N into urine is a significant factor causing spatial variation in N fixation rates.

Legume Growth

Legume growth in pastures is controlled by climatic and management factors, many of which also influence soil mineral N supply. However at any level of available soil N, legumes with inherent high growth rates fix more N than those of lower growth potential (e.g., Brock 1973). 'Grasslands Pitau' white clover produces more herbage and has higher N fixation rates than 'Grasslands Huia' white clover in grazed pasture (Crush et al. 1983), although Hoglund and Brock (1974) suggest that the symbiotic capability of Pitau lags behind its growth potential.

The seasonality of growth of legumes may interact strongly with soil mineral N supply patterns. Near Palmerston North, in mixed swards of white clover and 'Grasslands Pawera' red clover with grasses, the red clover tends to dominate over summer. However, N fixation efficiencies are very low at this time due to a combination of rapid mineralisation of soil N and low demand for N by grasses. In this mixed sward the major N fixation inputs come from white clover in spring when ryegrass is growing actively (J.R. Crush, unpublished data).

In a mixed sward, competition between grass and clover for light, nutrients and water has a profound effect on clover yield and N fixation. Some of these factors are amenable to management. Long regrowth periods after N fertiliser applications, or when growing hay crops, can exacerbate the effects of competition from grasses for minerals (Brougham et al. 1978). Depletion of urine patch N during hay growth can lead to very favourable conditions for legume growth and presumably N fixation following cutting.

We have assumed adequate nutrition of the legume during this discussion. It is worth emphasising the relatively poor competitive ability for nutrients of most legumes compared with grasses (Jackman and Mouat 1972).

Pasture Management

Pasture management systems that favour legumes will influence N fixation and N turnover in pasture. Legumes can be favoured by changes in grazing management (Bircham 1977) as well as changes in class of stock (Lambert et al. 1981, Clark et al. 1982).

Removal of most of the leaves from white clover results in a rapid decline in N-fixation activity. Minimum rates are reached within 1-2 days, and recovery is measurable after 5-6 days (Moustafa et al. 1969, Crush and Tough 1981). Defoliation effects are commonly interpreted in terms of reduced carbohydrate supply to nodules, but Hoglund and Brock (1978) suggest that in grazed pasture, increased soil mineral N and mineral N uptake by legumes may be additional limiting factors.

Brock et al. (1981) reported that N fixation in set-stocked white clover pasture was 37% higher from late spring to early winter than in a comparable rotationally grazed pasture. Regression analyses indicated that N fixation in the set-stocked pasture was controlled by legume growth rate and moisture supply, whereas under rotational grazing, legume growth and soil mineral N-related factors were most important. The explanation for these differences was that rotational grazing imposed severe stress on the plants, whereas under set stocking, plants were in better physiological condition and able to respond to short-term alleviation of moisture deficits.

Environmental Effects

Temperature and moisture supply influence legume growth and mineralisation as well as having some direct effects on nitrogenase activity. These factors are well documented for laboratory conditions. In the field situation, relationships between temperature, moisture, and net mineralisation of N are not established and are likely to be subject to local variations.

In pasture, soil moisture can cause extreme year-to-year variation in N fixation. Crouchley (1979) reported 90 and 240 kg/ha/yr N fixation in consecutive years in sheep pasture under uniform management. The second year was wetter and generally more favourable for legume growth. These results emphasise the dangers of short-term N research where the climate is unreliable.

There is a general latitudinal pattern of clover growth and N fixation in New Zealand that is governed by winter temperatures and summer moisture deficits (Hoglund et al. 1979). In general terms, in the north at latitude 35°S, winter temperatures are such that growth continues and seasonal variation in N-fixation rates is small. The farther south one travels, the more pronounced the spring peak in N fixation becomes.

Summer moisture deficits are common in all regions of New Zealand, but most pronounced in the east. The limited amount of data available suggests that summer irrigation sometimes has a relatively small effect on N fixation, despite a tendency for such pastures to become temporarily clover dominant (Crush 1979). On fertile soils the small N-fixation response to summer irrigation is explained by the effects of warmth and moisture on mineralisation at a time when grasses are in a slow, post-flowering phase of growth.

Two contrasting diurnal patterns of N fixation have been observed in field experiments in New Zealand, with white clover. One showed a considerable diurnal range and the other very little (Carran et al. 1982b). Soil temperatures seemed to be an important regulating factor some days, but not others. There may be strong interactions between the direct effects of soil temperature on nitrogenase activity and nodule energy status. Because the diurnal pattern of acetylene reduction (AR) activity by white clover may vary substantially from day to day, largely fortuitous relationships between AR activity and environmental factors may be derived when isolated days are examined.

Pests and Diseases

Until recently the effects of pests and diseases of legumes have received little attention in this country. White clover has been grown widely in New Zealand for over a century, allowing ample time for pests and diseases to arrive and adapt.

Parasitism of white clover roots by nematodes can drastically reduce growth of seedling clover (Healy et al. 1973) and established clover in pasture (Risk and Ludecke 1979). Steele and Shannon (1982) reported a 260% increase in acetylene reduction (AR) activity 3 months after nematicide treatment of a Northland beef pasture. Other trials in progress show substantial increases in AR activity when pests and diseases are chemically controlled (K.W. Steele, personal communication). The average increase in AR activity was 48%. These results indicate that pests and diseases of legumes may be very important factors affecting the legume-*Rhizobium* symbiosis in pasture.

Future Research

The general principles governing nitrogen fixation by grazed legumes growing in temperate pastures are well understood. It is possible to develop highly productive grass-clover pastures that are fully reliant on legume N fixation, by the application of current knowledge.

Future developments will require research into several areas. Soil mineral N influences symbiotic N fixation adversely in many developed pastures. Better procedures are needed to monitor both these characteristics, and their interaction. For N fixation the AR assay would appear to offer the best prospect.

The relationship between seasonality of growth and N fixation patterns for different legumes is not known, and this will have important implications for management of pastures.

The effect of pests and disease on legume N fixation has received little attention. A related factor, the introduction of tannin-containing legumes for stock health or pest resistance, may have deleterious effects on mineralisation rates for N in legume residues.

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Discussion

Roughley: Was acetylene reduction the N-fixation measuring technique used by all authors? Were the total amounts measured based on soil core extractions?

Crush: On the whole, yes, in answer to your first question and, basically, yes to your second. We interpret the data cautiously, especially in field studies. The validity of some acetylene reduction data has been checked against measurements made by "mass balance" methods.

Vallis: The figure for the proportion of clover N from fixation was surprisingly low. What proportion of the dry matter in the mixture was clover?

Brock: It was found, particularly in dry years when clover growth was reduced, that fixation was even more depressed because of the large contribution from mineral N. The contribution from clover to annual total yield ranged from 25% to 45%; and during the summer-autumn period, from 20% to 70%. Clover yield is greatly enhanced by a moist growing season.

Clements: Soil N has an overriding importance in depressing N fixation. Is there any selection work in New Zealand for N fixation under high N conditions?

Crush: We can only quote Hoglund's work. He is selecting white clover to maintain N-fixation rates under high N conditions.

Helyar: Grasslands is breeding to improve N fixation by clover at high levels of soil N. Is this not bad, because soil acidity may increase very quickly as the nitrate leaches?

Crush: The companion grass should take up the extra nitrate. Leaching losses probably stem more from urine patches than the background soil mineral N.

Brougham: There are a number of white clover breeding programs aimed at extending seasonality of growth in different circumstances. Part of the emphasis is to extend the growing season and hence N fixation. Surely it does not matter how N gets into the system, as long as it gets in.

Ball: Much of the nitrogen in the system is as ammonium, not nitrate. The soil is not acidified until nitrate leaches.

Reed: Do herbicides inhibit N fixation, and is there a screening system for this?

Crush: Herbicides appear to act not on N fixation but on clover growth. I am not aware of screening procedures.

Sheath: Clover's function is to build up and maintain soil N status. Is N fixation the limiting process, or is it the content of clover in the pasture?

Crush: N fixation processes per se are not limiting. The problem is maintaining enough clover in the pasture.

Knight: Would white clover lose its N-fixing efficiency in the same way as red clover did in the summertime (during its main growth period)?

Crush: Possibly, but white clover grows quite vigorously in spring. There are always grasses growing actively then, which use any excess soil mineral N.

Nitrogen Cycling in Legume-Based Forage Production Systems in Australia

Ian Vallis[1]

Abstract

Quantitative aspects of the nitrogen (N) cycle in legume-based pastures in Australia are reviewed. The yields of herbage N in tropical and temperate legumes in experimental plots cover a similar range, from less than 50 kg N ha^{-1} to approximately 500 kg N ha^{-1}. Inputs by symbiotic fixation in the field are best measured by N balance, i.e., by the summation of other inputs, losses of N and the net change in N content of the soil-plant-animal system. In the few such measurements that are available, the yield of N in legume herbage was only 45%-75% of the estimated N fixation, except in one case where the two quantities were about the same. The remainder of the fixed N was transferred to the soil or to associated grasses. The proportion of available herbage N ingested by animals in continuously grazed pastures is not well known, but the upper limits are probably 20%-50%. N returned to the pasture in urine is subject to losses by volatilization of ammonia, and these losses commonly reach 30%-50%. The remainder of the urine N is incorporated into soil organic matter, used by plants or subject to further losses. N returned in faeces would be expected to have small losses and low availability to plants, but field data are not available. Decomposition of ungrazed plant residues under temperate and subtropical conditions releases 20%-30% of their N for re-uptake by plants. Accumulation of nitrate in the soil profile under leguminous pastures during the dry season can reach 50-90 kg N ha^{-1}. Information is needed on the severity and frequency of losses of nitrate by leaching and denitrification in Australian pastures.

Introduction

The productivity of legume-based pastures is determined not only by how much nitrogen (N) the legumes fix, but also by how efficiently the dry matter and nutrients associated with this N are converted to animal products. Only a small proportion of the fixed N is retained by the grazing animals. The fate of the N that is returned to the pasture in plant residues and animal excreta influences the long-term effects of the legume on soil fertility and pasture productivity and is fundamental to the role of forage legumes as a source of N in pasture-crop rotations.

Most of the processes by which N is added to, recycled within, or lost from soil-plant-animal systems have been studied in detail, though usually in isolation and often under artificial conditions. This paper reviews the quantitative data on symbiotic N fixation, recycling of N and losses of N under field conditions. Several gaps in our knowledge of the N cycle are identified. The small inputs of N from non-symbiotic fixation, rainfall and direct absorption of atmospheric ammonia, and the effects of N fertilizers on N cycling are not considered.

Amounts of N Fixed by Legumes

Although the measurement of N fixation by legumes is simple in theory, accurate measurements in pastures under practical conditions are fraught with difficulties. The advantages and disadvantages of the many available techniques have been discussed in detail by LaRue and Patterson (1981). Field techniques can be put into three categories: (1) those based on yield of plant N, (2) those based on a N balance of the soil-plant-animal system and (3) those based on nitrogenase activity (acetylene reduction).

Yield Based Estimates of N Fixation

Yield based methods involve measurement of the total N uptake by the legume or legume-grass mixture and the proportion of that N derived from symbiotic fixation. The latter quantity can be determined by either the N difference method or the ^{15}N dilution method (LaRue and Patterson 1981). There are a number of potential errors and problems in these methods which must be guarded against. These are: (1) legume growth under cutting regimes may be different from that under grazing, and growth under grazing is difficult to measure (Davies and Trumble 1934; Linehan et al. 1952, Phillips et al. 1983), (2) the legume N may be recycled via grazing animals during the measurement period and therefore be measured more than once (Bryan 1962), (3) failure to measure the amount of N in roots, stolons and litter and (4) possible errors in the ^{15}N dilution method of measuring the proportion of legume N derived from symbiotic fixation (Witty 1983).

At present, there is no wholly satisfactory solution to the first two of the above problems in pastures that are grazed year-round or for prolonged periods. The problem is less serious, however, when legume growth is highly seasonal, the stocking rates are low and the young legume material is rejected in favour of grass, as with Stylosanthes spp. and Siratro (Macroptilium atropurpureum) in northern Australia (Hunter et al. 1976, Stobbs 1971, Gardener 1980). In such cases, peak legume yield in a growing season might be a reasonable basis for estimation of N fixation, provided the combined errors from sources (3) and (4) above are not too great.

Failure to harvest all of the accumulated plant N can be a serious error. Henzell (1968) estimated that with tropical legumes the N harvested in herbage usually accounts for only two-thirds of the total legume N, and Watson and Lapins (1964) found that herbage accounted for only 46 percent of the total plant N accumulated by subterranean clover (Trifolium subterraneum). In experiments in which herbage N was removed from the plots, the yield of N in legume herbage was 45%-75% of the estimated input of N by the legume, as estimated by a simple N balance (Watson and Lapins 1964, Crack 1972, Simpson

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1976), except in one experiment with a pure stand of S. humilis, where the two quantities were about the same (Wetselaar 1967). The remainder of the N input was transferred to the soil or the associated grass.

Australian work indicates that the proportion of legume N derived from fixation in established legume-grass swards is nearly always more than 80% and often greater than 90% (Vallis et al. 1977, Bergersen and Turner 1983). With pure swards of legume the proportion would, of course, be expected to decrease with an increase in the supply of available N (Allos and Bartholomew 1959).

One of the well-established concepts of the N economy of temperate pastures is that as soil organic N accumulates and the supply of available N increases, the legume will obtain less of its N requirement by symbiotic fixation and more from the soil (Brougham et al. 1978). With tropical pasture species, on the other hand, the evidence so far indicates that the grasses are very strong competitors for the available soil N, leaving insufficient N to impair N fixation by the legume (Vallis et al. 1977; I. Vallis and C.J. Gardener, unpublished data). It remains to be seen whether higher soil N status in older tropical pastures will have a significant, direct influence on the efficiency of symbiotic fixation.

From the above discussion, it follows that in mixed pastures the amount of soil-derived N in harvested legume herbage is usually less than the amount of legume N in the unharvested portions of the plants, and the yield of N in legume herbage is therefore a conservative estimate of the amount of N fixed.

In a review of sources of N for Queensland pastures, Henzell (1968) concluded that average growth of tropical legumes produced 30-140 kg ha^{-1} of herbage N, and good growth produced 220 kg ha^{-1}. His corresponding estimates of N fixation were 30-170 and 290 kg N ha^{-1}. These figures excluded the shrub Leucaena leucocephala cv. Peru, which in one season at Samford, S.E. Queensland, produced 576 kg N ha^{-1} in leaves and fine stems (Hutton and Bonner 1960). In the wet tropics of northern Queensland, L. leucocephala cvv. Peru and Cunningham produced 480 kg N ha^{-1} yr^{-1} in total top growth and 390 kg N ha^{-1} yr^{-1} in leaf growth (Ferraris 1979). In nineteen sets of experiments with S. humilis in northern Australia, the yield of herbage N by pure stands of legume was 30-220 kg ha^{-1} (average 110), and legume in mixed stands yielded 20-150 kg N ha^{-1} (average 60). Similar yields were recorded for S. guianensis, S. hamata and S. subsericea (Vallis and Gardener 1984).

Quite high yields of herbage N have been recorded for perennial, temperate forage legumes grown under irrigated conditions. Examples include: 250-500 kg N ha^{-1} for lucerne (Medicago sativa) (Teakle 1957, Kleinschmidt 1967, Simpson 1976) and 200-500 N kg ha^{-1} for white and red clovers (Trifolium repens and T. pratense) (Richardson and Gallus 1932, Kleinig et al. 1974, Simpson 1976). Yields for the annual subterranean clover are only 25%-50% of those for white clover (Kleinig et al. 1974, Simpson 1976). Under non-irrigated conditions, the yield of subterranean clover seldom exceeds 5 t ha^{-1} (dry matter) for short-season cultivars and 10 t ha^{-1} for long-season cultivars (Puckridge and French 1983). These yields would probably contain 150-250 kg N ha^{-1}. In Western Australia, short-season subterranean clover has yielded 17-125 kg N ha^{-1} yr^{-1}, excluding the establishment years, when yields were lower (Watson 1963, Watson and Lapins 1964, Watson et al. 1976). An annual medic pasture in South Australia was reported to yield 234 kg N ha^{-1} in pasture herbage (Puckridge and French 1983). In another study in South Australia, the average yield of three annual medics varied from 700-7000 kg DM ha^{-1} yr^{-1} between years (Amor 1966), and N yields would have been approximately 20-200 kg ha^{-1} yr^{-1}.

The above discussion indicates that the range of yields of herbage N and probable N-fixation rates in well-fertilized, infrequently defoliated tropical forage legumes is similar to that for the temperate legumes. Very little information is available on the actual rates of N fixation under farm conditions, but they are likely to be much lower than those in experimental plots (LaRue and Patterson 1981).

N Balance Estimates of Fixation

A simple mass balance equation for N fixation in grazed pastures is:

$$N_f = \Delta N_s + \Delta N_p + P + A + L - I, \qquad (1)$$

where N_f = N fixed,

ΔN_s, ΔN_p = change in N content of the soil and plant components, respectively,

P, A = N removed in plants and animals, respectively,

L = loses of N from the system, and

I = N inputs from other sources.

Major problems are: (1) it is not practicable to measure L in grazed pastures, (2) there is usually a large error attached to ΔN_s, and (3) there may be significant re-distribution of N in the soil profile. The latter two problems can be minimized by taking measurements over a long time-span and using appropriate controls. Thus, the numerous measurements of ΔN_s that are available for grazed pastures in Australia will only be a good guide to N fixation if losses (L) are small, and we shall see later that this is not usually the case.

The N-balance method is more easily applied to small plots of pasture where the herbage is cut and removed than to large plots of grazed pasture, because losses of N are minimized and the error attached to ΔN_s is smaller. The method was used to show that S. humilis fixed 93 kg N ha^{-1} yr^{-1} at Katherine, N.T. (Wetselaar 1967) and 77-120 kg N ha^{-1} yr^{-1} in north Queensland (Crack 1972). In southern New South Wales, fixation by subterranean clover, white clover and lucerne was 247, 474, and 510 kg N ha^{-1} yr^{-1}, respectively, when given supplementary irrigation (Simpson 1976).

Acetylene Reduction Estimates of N Fixation

Symbiotic N fixation by clover in pastures in Northern Ireland and New Zealand has been calculated from sequential measurements of hourly rates of acetylene reduction in the field (Halliday and Pate 1976; Hoglund and Brock 1978). However, no comparable measurements have been made in Australian pastures.

Recycling of N

Nitrogen returned to the soil-plant system in excreta and plant residues can either be incorporated into soil organic matter, taken up again by pasture plants or lost completely from the system. In mixed pastures, most of the re-uptake is usually by the grass, leading to the well known 'transfer' of N. However, this transfer is a function of the relative competitive abilities and growth patterns of the legume and grass species. For example, in mown plots, relatively greater transfer can be expected from annual legumes, where the plants die and decompose each year, than from perennial legumes (Simpson 1976). Apparent transfer in periodically grazed pastures can be 10%-39% of the yield of N in legume herbage (Jones 1967, Kleinig et al. 1974, Miller and van der List 1977).

Recycling Via Grazing Animals

The proportion of N recycled via this pathway obviously depends on the grazing pressure. Very few estimates are available, particularly for pastures that are continuously grazed. For a mixed tropical pasture of Verano (S. hamata) and native grasses grazed by 0.6 beef steers ha^{-1}, the estimated intake of legume N for a year was only 18% of the maximum N yield of standing legume (Vallis and Gardener 1984). Ebersohn and Lee (1972) suggested an average utilization of 40% of the dry matter for Queensland pastures, and at Canberra, Freer et al. (1970) estimated that the utilization of available forage by sheep during summer grazing was 13% in pastures stocked a 7.4 sheep ha^{-1} and 36%-51% at 29.7 sheep ha^{-1}.

The other factors determining the recycling of N are the retention of N in animals and the partitioning of excreted N between faeces and urine. These depend on the type of animal and the quality of the diet. In relatively productive beef and wool producing systems 87%-96% of the N ingested by animals is returned to the pasture in excreta. Approximately 47%-75% of the excreted N is in the urine, the percentage increasing with the N concentration of the diet (Henzell and Ross 1973). In table 1, the above figures for pasture utilization and N excretion are combined to show a range of possible returns of N via excreta.

Only limited information exists on the subsequent uptake by pasture plants of N returned in animal excreta. A significant proportion may be transferred to bare areas of ground where livestock congregate to rest or drink (Hilder and Mottershead 1963). Although the availability of urine N is potentially high, its uptake by pasture plants will be a function of the environment and the season of deposition. Annual ryegrass grown in lysimeters in a Mediterranean climate in Western Australia recovered 30%-50% of the N applied in urine, the lower recovery being for N applied early in the dry season and taken up in the following wet season (Watson and Lapins 1969). In north Queensland, 50%-70% of urea-^{15}N applied in urine remained as mineral N after 4 weeks and was thus potentially recoverable by plants (Vallis and Gardener 1984). However at Katherine, Northern Territory, although 30%-35% of the urea-^{15}N applied in urine remained in mineral forms at the end of the dry season, only 6% of the added ^{15}N was recovered by subsequent pasture growth (I. Vallis, D.C.I. Peake, R.K. Jones and R.L. McCown, unpublished data).

In contrast with N returned in urine, most of the N returned in faeces is in organic compounds that must be mineralized before the N can be used by pasture plants. The low availability of faecal N is illustrated by the results of a pot experiment carried out by Bornemissza and Williams (1970), in which plants recovered only 8% of the N from fresh

Table 1 - Retention and excretion of N by free grazing sheep or cattle as affected by pasture quality and for two levels of pasture utilization; the data are expressed as a percentage of the N available in the herbage

		Diet with 1.3% N		Diet with 3.5% N	
Utilization of Pasture N		18	50	18	50
Retention		1.8	5.0	0.9	2.5
Excretion:	urine	7.3	20.4	12.8	35.6
	faeces	8.9	24.6	4.3	11.9

Sources of data: Freer et al. (1970), Henzell and Ross (1973), Vallis and Gardener (1984).

cattle faeces added to the soil surface. Prior burial of the faeces by dung beetles increased this to 22%. The longevity of faecal pads and pellets in the field is clear evidence of the low availability of N from this source (Gillard 1967, Ferrar 1975, Rixon and Zorin 1978).

Recycling Via Plant Residues

It is clear from estimates of the efficiency of utilization of herbage in Australian pastures (Freer et al. 1970, Ebersohn and Lee 1972, Christie 1979) that more than half of the herbage N is usually returned to the soil in plant residues, although in intensively grazed systems the proportion returned in this way will be less (McKinney and Morley 1975). Actual rates of production of plant residues or litter vary enormously between environments, from about 1000 kg ha^{-1} yr^{-1} in semi-arid grasslands (Christie 1979) to 24,000 kg ha^{-1} yr^{-1} in a lightly grazed pasture in a humid subtropical environment (Bruce and Ebersohn 1982).

Many studies of the mineralization of N from plant materials have been made under laboratory conditions but only a few under field conditions, where moisture and temperature fluctuate and the geometry of the residue-soil system differs from that in laboratory studies. In a subtropical environment with 1050 mm annual rainfall, 7%-25% of the N in ^{15}N-labelled legume residues placed on the soil surface was taken up by one year's growth of a grass sward, the percentage depending on N concentration and species of residues. When uptake was low in the first year, proportionately more residue N became available in the second year, giving a total uptake over two years of 20%-30%. Uptake in the third year was small (Vallis 1983). These uptakes are similar to those by wheat (11%-28%) after ^{15}N-labelled residues of an annual medic were mixed with topsoil 5-8 months prior to sowing the crop (Ladd et al. 1981, 1983).

A complete appraisal of N return in plant residues should also include the root systems. Of particular interest is the release of N from root nodules. Roots and nodules of tropical legumes contain only 20%-30% of the plant N at the time of maximum yield (Whiteman 1971), but there is apparently some turnover of the nodule population through the growing season in response to defoliation (Whiteman and Lulham 1970, Whiteman 1970). The importance of roots and nodules is underlined by the substantial increases in soil N under plots where the legume herbage is removed (Watson and Lapins 1964, Simpson 1976). A precise separation of the contribution of N by above and below-ground plant parts under field conditions is experimentally difficult (Chamblee 1958, Bakhuis and Kleter 1965).

Losses of N

Volatilization of Ammonia

Relatively large losses occur by this pathway from sheep and cattle urine, with smaller losses from faeces and decomposing plant residues. Some measurements of losses in Australian pastures are shown in table 2. The losses in some of the N-balance experiments in table 2 may not have been wholly due to volatilization of ammonia, although supplementary measurements indicated that this was the main avenue for loss in the experiments at Canberra and Katherine.

Table 2 - Losses of N from urine or urea solutions in Australian pastures

Method	Location	Loss (%)	Reference
Flow-thru chamber	Armidale, N.S.W.	9	McGarity and Rajaratnam (1973)
Flow-thru chamber	Armidale, N.S.W.[1]	16	McGarity and Hoult (1971)
Flow-thru chamber	Brisbane, Qld	14-28	Vallis et al. (1982)
Micrometeorological	Canberra, ACT	26	Denmead et al. (1974)
N balance, lysimeters	Kojonup, W.A.	50	Watson and Lapins (1969)
N balance, pots		20-80	Watson and Lapins (1969)
^{15}N balance, microplots	Canberra, ACT[1]	60	Simpson (1968)
^{15}N balance, microplots	Lansdown, N. Qld[2]	18-32	Vallis and Gardener (1984)
^{15}N balance, microplots	Katherine, N.T.[2]	46	I. Vallis, D.C.I. Peake, R.K. Jones, and R.L. McCown (unpublished data)

[1]Using concentrated (20 g N L^{-1}) urea solution.

[2]Using urine enriched with urea-^{15}N.

Volatilization of ammonia from faeces of grazing animals has received much less attention than that from urine. Oven-drying can volatilize 8%-20% of the N in faeces (Falvey and Woolley 1974). In the field, an apparent loss of 80% from cattle faeces in a sub-humid tropical environment has been reported (Gillard 1967), but this seems very high and further work is needed to see if losses of this magnitude are common.

Ammonia can also be volatilized from decomposing plant residues. Laboratory incubations have indicated losses of 1%-30% (Salt 1965, Floate and Torrance 1970), the loss increasing with N concentration of the residues, but experiments estimating the loss of ammonia from plant residues decomposing in the field have apparently not been conducted.

Denitrification

Although the potential for denitrification in Australian pasture soils has been amply demonstrated in the laboratory (McGarity 1961; McGarity and Myers 1968; Stefanson and Greenland 1970, Myers and McGarity 1972; Stefanson 1972a, 1972b, 1972c, 1973; Catchpoole 1975), the magnitude of losses by this mechanism in the field is virtually unknown. The denitrification capacity of soils is strongly related to their content of water soluble carbon (Burford and Bremner 1975), and usually decreases with depth in the soil profile (McGarity 1961). However, in some Australian solodized solonetz soils an accumulation of leached soluble carbon may produce a high capacity in the upper B horizon (McGarity and Myers 1968).

Good aeration and low concentrations of soil nitrate would appear to be the two factors most likely to limit denitrification under Australian pastures. In poorly structured soils, rapid denitrification has been observed at moisture contents at or just below field capacity (Stefanson 1972a, 1972b), but in a better structured soil a moisture content above field capacity was required (Catchpoole 1975). The climate in most of the pastoral regions of Australia is such that these conditions would occur infrequently and be of short duration. Nevertheless McGarity and Rajaratnam (1973) suggested that intense microbiological activity following wetting of dry soils may induce significant losses of N by denitrification. This would be conditional on the supply of nitrate in the soil profile. Concentrations of soil nitrate in pastures without legumes remain low throughout the year (Martin and Cox 1956, Simpson 1962, Crack 1972), but in improved pastures containing annual legumes 50-90 kg ha^{-1} of nitrate-N may accumulate after occasional light rain during the dry season, when the pasture is dormant (Simpson 1962, Barrow 1969, Crack 1972, Bromfield and Simpson 1974). The potential for denitrification in grazed pastures is increased by the localized high concentration of nitrate that are produced under urine patches (Vallis et al 1982).

The recent development of the acetylene-blockage technique for field measurement of denitrification (Ryden and Dawson 1982, Ryden 1983) has opened the way for an evaluation of the practical significance of this mechanism of N loss in pastures. This technique blocks nitrous oxide reductase, permitting the use of N_2O evolution to estimate denitrification rate. The method does have several possible limitations, however.

Other Gaseous Losses

Nitrous and nitric oxide are apparently lost from soils during oxidation of ammonia, but the quantities are too small to be of agronomic significance (Galbally and Roy 1978, Freney et al. 1979).

Leaching

Quantitative data on leaching of nitrate under pastures in Australia is sparse. This deficiency can probably be traced to the need for either an extensive program of deep soil sampling or the use of deep lysimeters, both of which require considerable resources. In the discussion on denitrification, it was shown that substantial concentrations of nitrate can occur under leguminous pastures, so the possibility of significant losses by leaching warrants investigation.

There is evidence that nitrate accumulated during summer under improved pastures in southern New South Wales can be leached by heavy rains in late autumn and winter (Simpson 1962). Some quantitative information is available from relatively shallow (60-70 cm) filled-in lysimeters using light-textured soils in the south-west of Western Australia. Losses from a subterranean clover-grass mixture under an annual rainfall of 450 mm were only 2-7 kg ha^{-1} yr^{-1} (Drover 1963). The same author referred to unpublished experiments in which pure clover swards receiving 890 mm rain per year lost 55-220 kg N ha^{-1} yr^{-1}, which seems rather high. Seasonal effects are clearly shown by the leaching of N from urine applied to 70 cm deep lysimeters sown with annual ryegrass on sandy soils in south-western Australia (Watson and Lapins 1969).

Urine applied early in the growing season lost 1%-7% of the applied N, compared with no loss when applied in the middle of the season. When urine was applied after the growing season, heavy rains early in the next season leached 13%-17% of the applied N.

The combination of high temperatures and excessive rainfall during the wet season of the monsoonal areas of northern Australia appears to give the potential for large losses of N by leaching and denitrification. The magnitude and mechanisms of losses of N from urine patches, faeces and decomposing plant residues in this region represent a major gap in our understanding of the N economy of Australian pastures.

Soil N Balance

A number of equations describing the trends in the content of organic N in soils under different types of land use have been proposed (Stevenson 1982). One of the most commonly used to describe changes under pasture is that due to Jenny (1941):

$$\frac{dN}{dt} = -k_1N + k_2 \qquad (2)$$

Table 3 - Changes in soil organic N under various pasture legumes in Australia

Legume	Δ soil N ($kg\ ha^{-1}\ yr^{-1}$)	Reference
Temperate group:		
Trifolium repens	145	Jones et al. (1968)
	140	Kleinig et al. (1974)
	160	Simpson (1976)
Medicago sativa	112	Cameron and Mullaly (1970)
	107	Simpson (1976)
T. subterraneum	45 to 80	Williams (1970)[1]
Medicago spp. (annual)	10 to 40	Mullaly et al. (1967)
Tropical group:		
Macroptilium atropurpureum	130	Jones (1967)
	44	Vallis (1972)
	80	Johansen and Kerridge (1979)
Desmodium uncinatum	34 to 86	Henzell et al. (1966)
Glycine wightii	140	Johansen and Kerridge (1979)
Centrosema pubescens	122	Bruce (1967)
Peuraria phaseoloides	130	Bruce (1967)
Stylosanthes spp. (perennial)	45	Vallis and Gardener (1984)
Stylosanthes humilis	16	Wetselaar and Norman (1960)
	106	Wetselaar (1967)
	0 to 108	Crack (1972)
	-30 to +30	Vallis (1972)
	0	Myers (1976)

[1]A review of many reports.

where N is the content of soil organic N, k_1 is the proportion of that N mineralized and lost each year, and k_2 is the annual addition of N to the soil, assumed constant. In the present context, k_2 is taken to be mainly symbiotically fixed N, with only minor contributions from rainfall and non-symbiotic fixation. It is well recognized that k_1 and k_2 are unlikely to be constant (Russell 1975), but the equation has proved useful in analysing trends in soil organic N in some Australian pastures. For example, Russell and Harvey (1959) were able to show a probable annual input of 270 kg N ha^{-1} in clover pastures on reclaimed swamp soils of the lower Murray Valley, in which organic N approached an equilibrium value of 0.5% N. Several decades are often required to approach a new (higher) equilibrium value on soils with an initially low content of organic N, so the trends over the first few decades are often essentially linear (Russell 1960, Williams 1970). However, the changes vary from year to year, as would be expected with variable amounts of legume growth and N fixation, and an upward trend can be interrupted by a net loss during a dry season (Vallis 1972, Kohn et al. 1977). The accumulation of organic N usually increases with the amount of superphosphate applied until any deficiency of P and possibly S has been corrected (Donald and Williams 1954, Russell 1960, Henzell et al. 1966, Watson 1969).

Some rates of change in soil organic N in Australian pastures are given in table 3. The data for tropical and temperate areas are similar except for the greater prevalence of zero and negative values from the tropics.

The supply of available N rather than the total N content of the soil will determine pasture growth. Small changes in total N content can result in relatively large changes in readily available N (Greenland 1971), and available N may even increase where there is no net change in total N (Myers 1976). Availability of N may be higher under higher grazing pressures (Bromfield and Simpson 1974).

Research Needs

There are good data for some of the major quantitative aspects of the N cycle in Australian pastures. These include:

1. Yields of nitrogen and probable amounts of fixed N under good conditions in mown or periodically grazed swards.
2. Volatilization of ammonia from urine patches.
3. Mineralization of N in residues of pasture plants in temperate and subtropical regions.

Aspects of N cycling for which research is needed to better define the flows of N include:

1. Growth and N fixation by legumes in pastures under normal (continuous) grazing.
2. Utilization of pasture growth by grazing animals and thus the proportionate returns of N to the pasture in urine, faeces and plant residues.
3. Mineralization of N in plant residues in tropical areas.
4. Losses of N by denitrification and leaching.
5. The effect of increased availability of N with pasture age on the efficiency of N fixation in tropical pastures.

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Discussion

Syers: Vallis mentioned that water balance models with nitrate models would be useful. Scotter and Gregg are developing such models at Massey University, Palmerston North, N.Z.

Syers: You estimated that pasture N utilization in Australia was 20%-40%. This is low by N.Z. standards. With such low figures, does it not follow automatically that plant residues are likely to be important?

Vallis: Yes.

Syers: Grazing may affect the rate of breakdown of litter and be important to your result. Have you thought about this?

Vallis: Have certainly thought about it, but have not measured.

Ball: Best estimate of Harvest Index (70%) in clover gives about 40% harvest of available N_2 (from a trial cut about every 3 weeks or longer rotations). The rest (60%) is through decay or turnover through slugs, etc.

Nitrogen Cycling in Legume-Based Forage Production Systems in New Zealand

Keith W. Steele and John L. Brock[1]

Abstract

Grazing animals have a dominating effect on nitrogen (N) cycling in temperate pasture ecosystems through the return of biologically labile N in excreta. Under extensive agriculture, pasture plants are largely dependent on mineralisation of soil organic matter or N fixation to provide their N requirements for growth. As pasture productivity and animal stocking rate increase, however, animal excreta contributes proportionally more to the N taken up by pasture plants. Urine is a high risk compound for N loss, and uptake of urinary N in pasture herbage is generally 30 percent or less. The amount of N loss from pasture ecosystems generally increases with increasing productivity. To sustain productivity, N inputs, largely through symbiotic fixation, must equal N losses. Many management practices affect symbiotic N fixation, N transformations and N losses. The effect of management, concept of N balance and implications of a change in total ecosystem N are discussed.

Introduction

Nitrogen (N) cycling in temperate pasture ecosystems is complex and dynamic, including inputs, outputs, various pools of N within the ecosystem and exchanges and transformations of N between pools. The amount of N in various pools and rates of exchange between pools vary by several orders of magnitude (fig. 1). The two pools of organic matter appear to have differing roles. The smaller labile pool is more involved in short-term effects on production. For example, in a "soil fertility building" sense, this pool appears to be satisfied relatively quickly (2-3 years) as estimated by growth responses. On the other hand accumulation of N in the stable pool can continue for many years (>25 years) and is more associated with long-term productivity and stability. The soil microbial biomass, as the agent for decomposition, occupies a key position, acting both in supplying nutrients for current production and exchange between the other pools. Overall, to sustain a given level of pasture productivity there is a need to achieve a long-term N balance in the ecosystem. Short-term imbalances may be masked by changes in the size of the soil organic N pool which may exceed 1.6 kg N/m^2 (to soil depth of 15 cm) and accounts for more than 95% of total ecosystem N. Therefore

$$\text{N inputs} - \text{N losses} \pm \Delta \text{ Total ecosystem N} = 0.$$

Nitrogen Inputs

In high producing pastures symbiotic N fixation by the Rhizobium-legume symbiosis accounts for more than 90% of total N inputs, excluding fertiliser N. Inputs via asymbiotic fixation and precipitation are minor, contributing less than 15 kg N ha^{-1} yr^{-1} (Sears et al. 1965, Ball 1979) but may assume importance in some extensive hill country pastures (Lambert et al. 1982).

In legume-dominant pastures on soils of low N status, annual symbiotic fixation may exceed 500 kg N ha^{-1} (Steele 1982). However, as mineral N concentrations increase, annual symbiotic fixation

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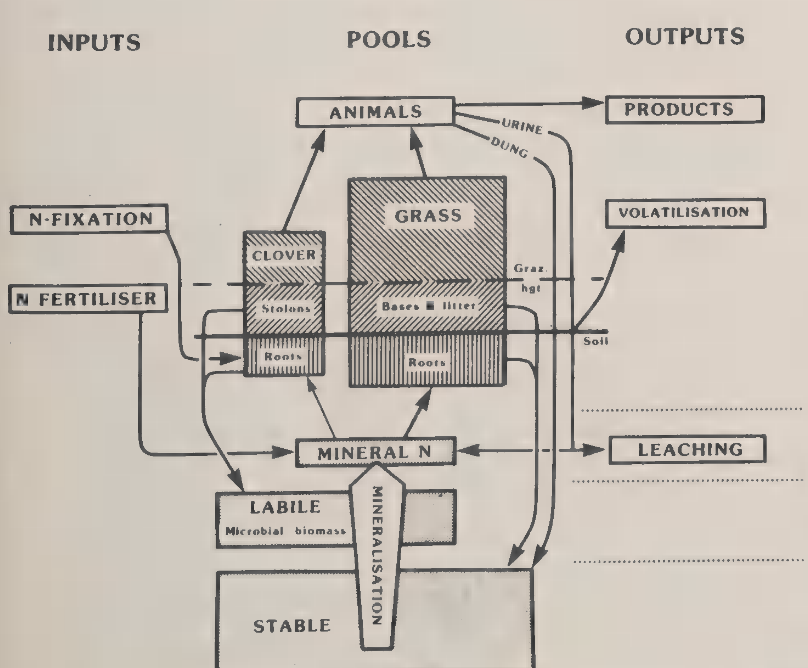

TURNOVER RATES	EFFECTS ON CYCLING	EFFECTS ON TOTAL SOIL N	GRAZING EFFECTS INTENSIVE	GRAZING EFFECTS EXTENSIVE
FAST (Days-weeks)	LARGE	SMALL	+	−
MEDIUM (Months-year(s))	MEDIUM	LARGE	+	−
SLOW (Years-millenia)	SMALL	LARGE	−	+

Figure 1--Major pools and flows of N in legume-based forage production systems.

falls to between 100 and 300 kg N ha^{-1} representing approximately 28% of the total N flux through the pasture as measured at a range of sites (Hoglund et al. 1979, Hoglund and Brock 1984). Soil moisture deficits, insect pests, return of animal excreta, and cyclic and management-induced changes in the legume content of pastures may further reduce N fixation (Scott 1977, Steele and Shannon 1982).

Tactical applications of fertiliser N may be used to complement biologically fixed N and overcome short-term feed deficits for stock. However, the total annual input of fertiliser N to N.Z. pastoral agriculture is small (8000 t) relative to biological fixation (>1.1 million t) (Cullen and Steele 1983).

Nitrogen Losses

Nitrogen may be lost from pasture through ammonia (NH_3) emission from soil, fertiliser, animal excreta and plant material; as N_2 or N oxides by biological and chemical denitrification and fire; in solution via leaching and surface runoff; by retention in livestock; removal in animal products; by transfer to non-productive areas in livestock excreta; and through removal of particulate material in air and water (Steele 1984). Estimates of the annual loss of N from N.Z. pasture ecosystems via the various pathways vary widely (table 1).

Three general principles apply to N loss:

1. Excluding animal retention, transfer and products, mineral N (NH_3, NH_4^+, NO_2^-, NO_3^-) is intermediary in all major pathways of loss;

2. The magnitude of loss depends on the size and rate of turnover of the mineral N pool; and

3. Herbivores play a dominant role in influencing both the magnitude and pathway of loss from grazed pastures.

The Influence of Herbivores on N Cycling

Grazing animals separate much of the ingested N from plant carbon and excrete it in a biologically labile form in urine on small areas, in which N concentrations exceed those which plants can utilise (Ball 1979). Many N.Z. studies conducted over a wide range of seasonal temperature and rainfall conditions have shown that recovery of urinary N in pasture herbage is generally 30 percent or less (During and McNaught 1961, Ball et al. 1979, Ball and Keeney 1983, Ledgard et al. 1982, Ledgard and Saunders 1982). Only a small proportion of N is likely to be immobilised into the soil organic fraction (Steele et al. 1980) and loss of N is generally large. Since denitrification does not appear to be an

Table 1 - Estimated nitrogen losses from pasture ecosystems in New Zealand

Stock type	sheep	sheep	dairy cattle
Stocking rate (SU ha^{-1})	6	20	24
Land class	unimproved hill country	irrigated flat-land	intensive dairy
Pasture production (t DM ha^{-1} yr^{-1})	3.27	11.00	16.50
Nitrogen Losses			
NH_3 emission from:			
Soil	) 4		
Animal urine	)	10	20
Animal faeces	)	10	4
Plant materials	)	10	
Biological denitrification	)	10	30
Leaching		100	110
Surface runoff	10		
Retention in livestock		20	8
Removal in livestock products	4		66
Transfer to non-productive areas		30	46
Total	18	190	284
Reference	Lambert et al. 1982	Quin 1982	Steele 1982

important pathway for loss of N from urine (Limmer and Steele 1983), N loss will occur primarily through NH_3 volatilisation (Ball and Keeney 1983) or leaching (Steele et al. 1984); the partioning depending on prevailing climatic conditions as well as soil and pasture parameters.

Under extensive agriculture, pasture plants are largely dependent on mineralisation of soil organic matter or N fixation to provide their N requirements for growth. As pasture productivity and animal stocking rate increase, animal excreta contributes proportionally more to the N taken up by pasture plants (fig. 2). For example, on rotationally grazed dairy farms stocked at 4 cows ha^{-1}, on average 45% of the grazed area is affected by animal excreta at any one time and this produces 70% of total annual dry matter production (W.M.H. Saunders, unpublished data). In comparable cut vs. grazed ryegrass/white clover swards in the Manawatu, utilised herbage production was 15.1 and 18.1 t ha^{-1} yr^{-1} respectively over 3 years (Ball 1979), or 20% greater due to animal return. Despite the substantial N losses that occur from urine patches at high stocking rates, animal excreta is important in maintaining high pasture productivity.

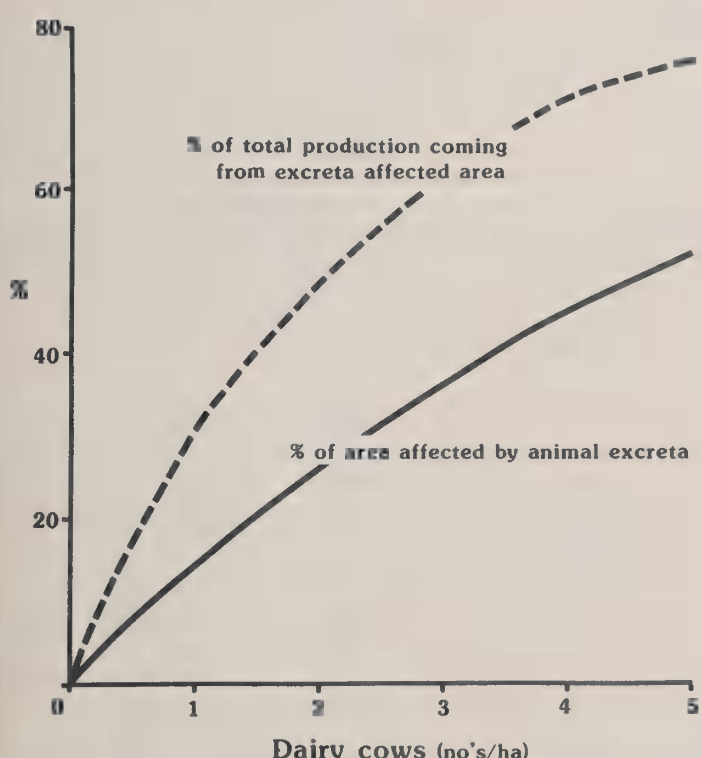

Figure 2—The influence of dairy cow stocking rate (numbers/ha) on:
(i) the percentage of paddock area affected by excreta and
(ii) the percentage of total forage production coming from excreta-affected areas.

Management Effects on N Cycling

Grazing Management

Fencing to prevent transfer of animal excreta to non-productive areas or stock-camp sites and to improve excreta distribution will improve distribution and cycling of N. As a result of intensive defoliation under rotational grazing, plants suffer severe "physiological shock" and are less able to utilise the large return of available N via the animal and senescing tissue. The available N is therefore at high risk should the environment encourage losses. Set stocking, with frequent though lenient defoliation, maintains the sward in a more uniform physiological state; better able to cope with the less frequent animal return over a large time span. This results in lower levels of herbage NO_3-N in set-stocked than rotationally grazed pastures in all seasons except winter (table 2). Pasture cover has been shown to affect NH_3 volatilisation losses (Kresch and Satchell 1960, Freney et al. 1981), in which case the denser, set-stocked pastures could be expected to have smaller NH_3 losses relative to the more open, rotationally grazed pastures. Cattle, with their higher volume and greater aggregation of excreta, increase the potential for N loss from the urine patch relative to sheep (Jackman 1960).

In recent years more emphasis has been placed on the role of litter decomposition in N cycling (Ball et al. 1979, Carran 1979). Increasing pasture utilisation effectively reduces cycling through the litter pool, increasing the dependence of plants on mineralisation of stable soil organic matter and animal excreta for their N requirements. Should N inputs be insufficient to keep pace with losses, a negative N balance will result, at least in the short term (Field and Ball 1982). Accumulation or depletion of the labile and stable soil organic N pools appears to depend on the amount of N cycled through the litter pool. Rotational grazing of pastures to 500 kg residual DM ha^{-1} resulted in a loss of 30 kg soil N ha^{-1} yr^{-1} compared with a gain of 130 kg soil N ha^{-1} yr^{-1} when grazed to 1,200 kg residual DM ha^{-1} (J.H. Hoglund, unpublished data). In another trial total soil N fluctuated 200 kg N ha^{-1} yr^{-1} around the mean under rotational grazing, but showed only a 50 kg ha^{-1} yr^{-1} variation under set stocking (J.L. Brock, unpublished data). Changes in the labile pool, as indicated by soil biomass, showed higher levels of both biomass carbon (C) and mineral N flush under frequent than infrequent rotational grazing (R.A. Carran, unpublished data) and of mineral N flush under set stocking than rotational grazing (J.L. Brock, unpublished data). Dense, set-stocked pastures have lower proportional availability to grazing animals compared with the more open, low-density pastures created by rotational grazing. At comparable stocking rates pasture residues are twice as high under set stocking as under rotational grazing (2,900 vs. 1,500 kg DM ha^{-1} annual mean; J.L. Brock, unpublished data). Set stocking would appear to have the advantage in terms of maintaining soil organic matter in the long term, but this must be balanced against the greater flexibility of feeding supply and control made possible by rotational grazing, particularly during early lactation and mating when animal feed requirements are high.

In New Zealand, up to three-quarters of total annual pasture production may occur during the spring-early summer period. This coincides with the time of

Table 2 - Comparison of herbage NO_3-N concentrations (ppm) in clover and grasses under rotational grazing (Rot) and set stocking (SS) (Brock et al. 1983)

		Spring	Summer-Autumn	Winter
Clover:	Rot	210	330	220
1975-6	SS	195	455	200
1976-7	Rot	395	370	190
	SS	150**	235*	175
1977-8	Rot	330	414	
	SS	250**	180**	
Grasses:	Rot	670	790	1,035
1975-6	SS	765	880	800*
1976-7	Rot	1,165	1,195	1,145
	SS	550**	715***	1,015
1977-8	Rot	1,150	1,155	
	SS	915**	495**	

*, **, *** = Grazing treatment effect significant at 5, 1 and 0.1% level respectively.

highest animal production, deposition of excretal N, N fixation and soil microbial activity. Management practices during this period may be expected to have a major impact on annual N budgets.

Botanical Composition

The critical C:N ratio of plant material below which rapid decomposition and release of N occurs, and above which immobilisation takes place, is in the 20-25 range for root material (Whitehead 1970). Clover tissues have C:N values generally below 20, while grasses are generally above 30. Legume material therefore is more important to the labile pool and short-term production, and grasses with the long-term, stable pool (fig. 1).

As a consequence, changes in botanical composition towards increasing legume dominance would be expected to increase the available N pool, and hence current production, but also increase losses. Rotational grazing is more likely to allow higher legume content but may also result in some loss of stable soil organic matter, with the converse for set stocking.

Plant Species

Both white clover and perennial ryegrass, the traditional components of N.Z. pastures, are at the lower end of the C:N ratio for temperate pasture legumes and grasses (approximately 12 and 30-35 respectively; Whitehead 1970). That is, they can be considered to produce the highest quality organic matter for rapid cycling. This is supported by biomass C and mineral N flush values, respectively being 13% and 12% higher in soils under ryegrass/white clover pastures compared with cocksfoot-dominant pastures (J.L. Brock, unpublished data). Species with a higher inherent C:N ratio (lotus and lucerne, table 3) may ameliorate the higher losses, particularly under rotational grazing, by providing a larger, more stable pool of organic matter resistant to decomposition.

Soil N Balance

Any change in a parameter such as grazing pressure will result in a move towards a new equilibrium level of total ecosystem N. Unfortunately no sufficiently detailed, long-term studies have been reported to establish the implications of movement to a new equilibrium level of total ecosystem N. One may question the necessity of maintaining the levels of soil organic N present in some N.Z. soils. Do the high soil organic N levels reflect an inefficient utilisation of pasture herbage?

Pasture ecosystems will move to compensate for any induced change. Declining available soil N concentrations outside excreta-affected areas will prompt an increase in clover growth, N fixation and mineralisation of plant litter.

Future Research

Four approaches may be taken to increase pastoral production through a reduction in N deficiency:

(i) Increased inputs of fertiliser N. Although some increase in fertiliser N use in New Zealand is likely to occur, this will be through an increase in tactical dressings. At current costs, large N inputs to pasture are uneconomic.

Table 3 - Recovery or transfer of N to grasses from various forage legumes (kg N/ha/yr)

	Total N fixed	Soil	Recovery 1st year	2nd year
New Zealand (Brock 1973)				
White clover	570	130	92	68
Lotus	590	200	78	76
Suckling clover	265	75	56	66
Australia (Simpson 1976)				
White clover	475	190	30	
Lucerne	510	120	16	
Sub. Clover	250	100	50	

(ii) Increasing inputs of N through biological fixation. There is an urgent need for breeding or selection of a legume-Rhizobium symbiosis which is (a) more competitive with associated grasses and therefore able to maintain a larger contribution to total DM production from the pasture and (b) able to maintain N fixation in soils which contain high and widely fluctuating concentrations of mineral N.

(iii) Increasing production/unit of N input. This is the most acceptable long-term approach. There is a need for further research to identify and understand the mechanisms of N loss in agricultural systems and to develop management practices to conserve N.

(iv) Research is required to identify differences in importance of various portions of the N cycle (particularly the labile or biomass pools). Better understanding of the influences of management practices should allow manipulation for greater productivity or conservation of organic matter.

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Discussion

Ball: Your estimates for the areas responding to dung and urine are out of line with some literature figures by a factor of almost two. Are the responses to N only, or is there an influence of other nutrients, for instance K or P?

Steele: The estimates we have given are the proportions of a paddock affected by excreta at any given time. On average, 45% of the total area is affected by excreta, and this produces 70% of annual DM. The effect appears to be due to N and not other nutrients. In a urine patch, there is early dominance of grass followed by clover dominance. The faecal areas would maintain a higher initial clover content.

Ball: How long would the excreta patches influence production?

Steele: Averaged over dung and urine-affected areas, about 33 weeks.

Sheath: Is the discrepancy in viewpoint between Ball and Steele possibly due to a difference in measuring technique, removing uneaten herbage or not?

Steele: I don't think so.

Clements: I have been working with Reg. Keogh on grazing preference by sheep for faeces- and urine-affected areas of pasture, at stocking rates equivalent to those described. Our results for pasture performance agree substantially with those from Keith Steele, but measurements were confined to a 6-month period.

Syers: Would you comment on the usefulness of biomass N as an index of available N?

Brock: I have collected a lot of data on biomass N for a "look-see," but have not yet determined how to interpret it. It was originally measured as a parameter to explain variation in N fixation models, which has yet to be done.

Syers: We have used biomass P as an index of P availability and this has been very disappointing.

Mineralization of Nitrogen from Legume Residues

Dennis Keeney[1]

Abstract

The mineralization-immobilization turnover (MIT) concept is reviewed in light of recent experimental findings and theory. MIT is continually occurring in soil, with C and N flowing from plant residues and incorporated organic matter through the biomass. Net N mineralization occurs rapidly with legume residues. Decomposition is characterized by a rapid phase (a few weeks) of C and N release followed by a slower release rate that eventually approaches recalcitrant soil organic matter. The active phase, consisting of fresh residues, soil biomass, and recently incorporated organic N, degrades much more rapidly than the bulk soil organic N. These concepts aid greatly in our understanding of changes in pasture composition, transfer of N from legumes to grasses, loss of N from intensively managed pastures and the short-term nutritional benefits of tillage and cropping of legume-based systems.

Introduction

The central role of N in production of quality forage has long been accepted. In 1905, Vorhees and Lipman wrote:

> It would not be out of place here to express the hope that with our broadening knowledge we shall find means to provide for a better conservation of the soil nitrogen, whether it be by soil inoculation with vigorous cultures of symbiotic and non-symbiotic nitrogen-fixing bacteria, or by an intelligent maintenance of the nitrogen balance in the soil, so as to prevent the unnecessary dissipation of combined nitrogen through the one-sided activities of the decay bacteria.

Can our objectives be expressed any better today?

Legume-based forage systems and pastures rely largely on symbiotic N fixation as the N source for the legume and for the associated grass. Perhaps nowhere else is this system so finely tuned as in the intensively managed New Zealand ryegrass-white clover pastures (Ball and Field 1982). Yet N deficiency is a common occurrence, and it has been estimated that pasture production could be doubled if this deficiency were corrected (Steele 1982).

The net mineralization of N from legume residues plays a central role in forage productivity. Organic matter accumulates over time, leading eventually to high net N mineralization. Low N fixation efficiency and grass dominance exemplifies this phase of pasture development (Brougham et al. 1978). Insufficient available C is present to immobilize N aggregated in urine patches, and substantial N losses through the inorganic N pool are likely (Ball et al. 1979; Field and Ball 1982; Ball and Field 1982; Ball 1982, 1984; Carran et al. 1982; Ball and Keeney 1983).

The yearly flows of N through an intensively managed forage or pasture system are large relative to those for most cultivated systems, with total plant N uptake in the 300 to 700 kg ha^{-1} range (Field and Ball 1982, Ball 1984). Depending upon specific circumstances, much of this N will come from the soil available N pool. The modern view is that in pastures, mineralization of residues and recently incorporated soil organic N rather than return of animal excreta are the dominant source of this N (Vallis 1978, Ball 1982, Ball and Ryden 1984). Mineralization of recently added plant residues is also a key to the recovery of N on cropping of soils and will become increasingly important as emphasis switches to development of cropping systems less dependent on energy-intensive commercial N fertilizers (Heichel and Barnes 1984). It is my objective to dissect the mineralization-immobilization turnover (MIT) phenomenon with particular emphasis on low C/N legume residues.

The Mineralization-Immobilization Process

The mineralization-immobilization concept had been clarified by the mid-1930's (Bartholomew 1965). It was generally accepted that the C/N ratio for net mineralization was about 25:1, and that plant composition, particularly of refractive C compounds, was involved. Advances in tracer techniques, the soil biomass concept, and the recognition of active and passive fractions of soil organic matter, along with the recognition that NH_4^+ is central to microbial growth and decomposition reactions, has formed the basis of unifying the internal cycle (Jansson 1958, Paul and Juma 1981, Jansson and Persson 1982).

Since this cycle is heterotrophic, flows of C are intimately linked with N. Mineralization and immobilization are basic functions of the heterotrophic biomass. Ecologically, mineralization results in NH_4^+ release and energy dissipation from the organic matter. The NH_4^+ will be partly immobilized in microbial tissues, partly taken up by plants (autotrophic subcycle, fig. 1) and partly nitrified and denitrified (elemental subcycle fig. 1). The mineralization and immobilization processes work in opposite directions, to produce either net mineralization or net immobilization. Net mineralization dominates, but some immobilization through the biomass is always occurring (Keeney and Gregg 1982). Hence, the measurements of only net effects (for example, mineralization tests for N availability), while of practical importance, provide little information on the magnitude of turnover processes actually occurring.

Lack of appreciation of this continuous turnover through the biomass has led to confusion with regard to interpretation of tracer data, and in particular the "priming effect," wherein the tracer N or C is exchanged for nonlabeled N or C in the active pool.

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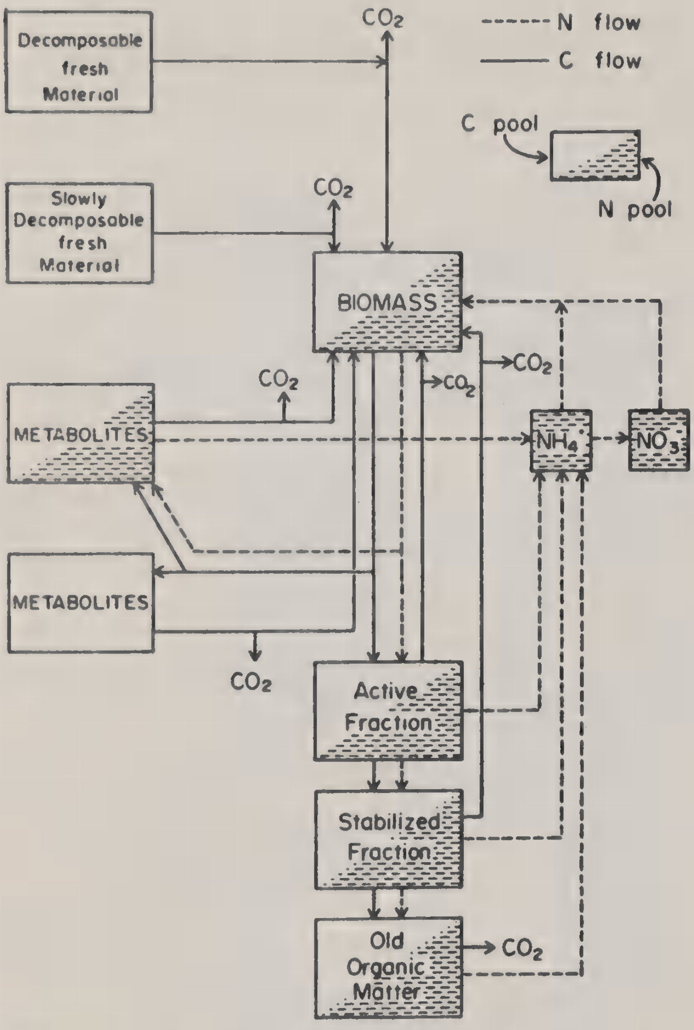

Figure 1--The Universal N cycle divided into its three subcycles: the elemental (E), the autotrophic (A), and the heterotrophic (H) (Jansson and Persson 1982). Reprinted by permission of the American Society of Agronomy, Inc., Madison, Wisconsin.

The net "apparent" effect of additions of fertilizer N or organic matter is often an increase or decrease in mineralization of soil organic N or C (see Jansson and Persson 1982).

Environmental effects on net mineralization are not as great as one might expect (Bartholomew 1965). Temperature in the mesophilic range speeds or slows biological activity, with a Q_{10} (the ratio of reaction rate constants) at >10°C of about two (Stanford et al. 1973). Suboptimum moisture also slows turnover, whereas freezing-thawing or wetting-drying can stimulate mineralization (Jansson and Persson 1982).

Phases of Soil Organic Matter

Modern concepts of MIT utilize the phase concepts of soil organic matter (Jenkinson and Rayner 1977, Jansson and Persson 1982; fig. 2). The large passive phase involves organic residues relatively resistant to microbial attack (the soil humus) with a turnover rate so low (half-lives in 10^2 to 10^3 years) that this heterogeneous fraction is not

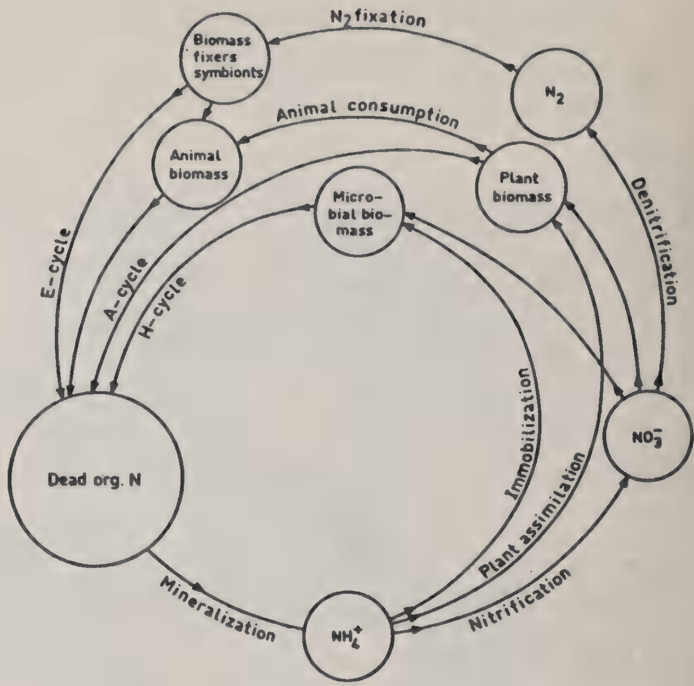

Figure 2--Flow chart for transfers of C and N in soil (Paul and Juma 1981). Reprinted by permission of the Swedish Natural Science Research Council, Stockholm.

involved in short-term N cycling from a practical standpoint. Of more immediate interest are the active phases, the fresh plant residues, recently incorporated biomass, and recently incorporated organic matter. These have short half-lives (weeks to 1 or 2 years) and thus comprise the N available for short-term recycling or release to a subsequent crop.

Evaluation of MIT in Legume-Based Systems

Numerous studies have been conducted in an attempt to develop methods for measuring these fractions and models of their dynamics. Isotope labeling of the N and preferably also of the C is essential. Often, inorganic N is added to soils (usually in conjunction with available C such as glucose) and these phases allowed to equilibrate before fractionation or perturbation. The other approach is to add single or dual-labeled plant material. However, use of plant residues leads to problems of handling and placement (Till et al. 1982).

The picture that is emerging is reasonably consistent among researchers and with theory. Legume-residue decomposition as measured by $^{14}CO_2$ evolution and residual organic ^{14}C consists of at least two distinct phases, a rapid phase lasting in the vicinity of 2 to 6 weeks (depending on soil and environmental conditions) and a slow phase with declining rates of decomposition approaching with time that of the recalcitrant (old) organic matter. Net N mineralization follows the same pattern but relatively more C than N is mineralized. This is shown in fig. 3 which gives results of a 4-year field experiment in South Australia (Ladd et al. 1981a) where ^{14}C–^{15}N-labeled medic tissue (Medicago littoralis; C:N, 25.3:1) was mixed with soil and kept under fallow. The soils

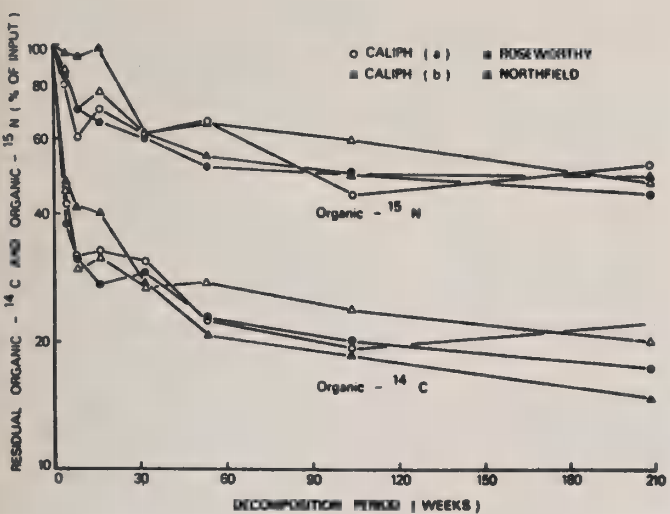

Figure 3—Decomposition of ^{14}C, ^{15}N-labeled legume residues in four field soils (Ladd et al. 1981a). Reprinted by permission of the Pergamon Press, Oxford.

were of the same pH but differed in texture and organic matter, and two of the sites had twice the rainfall as the others. Despite these differences, the decomposition patterns were markedly similar and resembled closely the decomposition curves with ryegrass obtained by Jenkinson (1977a). More than 50% of the ^{14}C was lost after 4 weeks, and only 15% to 20% remained after 4 years. About 35% to 40% of the organic ^{15}N had been mineralized at 32 weeks and 40% to 50% after 4 years.

The soil biomass is continually receiving inputs from decomposition of labile dead organic matter and is declining due to microbial death (Marumoto et al. 1982). In the Ladd et al. (1981a) experiment, biomass C and N increased rapidly and was maximum in 4 to 8 weeks. About 14% of the residual organic ^{14}C and 22% of the residual organic ^{15}N was in the biomass fraction at this time. From 8 to 52 weeks, the labeled biomass declined rapidly, followed by a slower decomposition rate to 4 years. However, the biomasses ^{14}C and ^{15}N were more labile than the residual organic ^{14}N and ^{15}C.

These results confirm others that the biomass C and N declines disproportionately faster than the bulk of the recently incorporated residue (Jenkinson and Rayner 1977, Ladd et al. 1977, Amato and Ladd 1980). It is truly the "eye of the needle through which all natural organic materials must pass, often more than once, as they are degraded to inorganic compounds" (Jenkinson 1977b).

Vallis (1983) applied ^{15}N-labeled legume materials of various N concentrations to the surface of a Rhodes grass pasture in subtropical southeast Queensland to simulate litter deposition. Data for two experiments with dried Macroptilium atropurpureum c.v. Siratro leaves are given in table 1. For no obvious reason, ^{15}N recovery in the second experiment was much lower than in the first experiment. Importantly, about half of the remaining N was incorporated in the soil (0-15 cm) and considerable of the legume N had been transferred to the grass. When urine or inorganic forms of N such as urea are added to pastures at high rates, immobilization is much less and the turnover rate of the inorganic pool is rapid (Keeney and Macgregor 1978, Ball et al. 1979).

The mechanism of transfer of legume N to grass has been a source of confusion for years. In addition to the obvious, but now recognized as inefficient, deposition of dung and urine in grazed pastures, underground transfer of N involving death and mineralization of legume roots and nodules was assumed to be the main mechanism (Walker 1956). Later research has suggested that this mechanism was overemphasized (Vallis et al. 1977, Sinclair et al. 1977). It is now recognized that in pastures the death and decay of aerial tissues is equally

Table 1 - Percentage recovery of ^{15}N applied in Siratro leaves to the soil surface of a Rhodes grass sward (Vallis 1983)

			Component (% recovery of ^{15}N)				
			Plant				
Experiment	Time (yr)	Material	Tops + stubble	Roots	Litter	Soil	Total
1	1	Low N[1]	7.3	5.6	34.2	52.8	99.7
	2		22.4	7.1	3.7	44.2	79.0
2	1	Low N[1]	8.4	4.5	15.0	22.7	53.5
	1	High N[2]	18.1	6.7	7.6	25.0	58.9

[1]Leaves contained 1.35% N.

[2]Leaves contained 3.84% N.

Table 2 - Percentage distribution of ^{15}N from medic residue added to soil (Roseworthy site) and cropped to wheat (Ladd et al. 1981b)

Component				
Plant		Soil		
Grain + stover	Roots	Inorganic	Organic	Total
16.7	0.6	3.1	71.9	92.3

important (Brougham et al. 1978, Vallis 1979, Field and Ball 1982, Carran 1983), where the N and C enter the internal N cycle. Stewart and Chestnutt (1974) noted that the N made available to a grass was more related to the previous year's than the current year's clover N. Trampling by livestock may enhance incorporation of readily degradable legume residues (Till et al. 1982).

Ladd et al. (1981b) described an experiment where the autotrophic N cycle (plant uptake) was combined with the heterotrophic cycle. ^{15}N-labeled medic material was mixed with topsoil and allowed to decompose for 8 months before planting to wheat. The ^{15}N distribution after harvest at one site is given in table 2; results at two other sites were similar. As in the experiment by Vallis (1983), ^{15}N recovery by the plant was relatively low (17%). The wheat plants took up only the equivalent of 1.85% of the soil total organic N, illustrating the much greater availability of N in legume residues compared to the bulk organic N pool. They also calculated, using the uncropped medic decomposition data (fig. 3), that some net immobilization of ^{15}N had taken place during the cropping phase. This agrees with the findings of Huntjens (1971), who demonstrated that net immobilization occurs in the root zone of permanent grasslands, and that this N is subsequently more readily mobilized than the bulk soil organic N.

Perspective

The foregoing discussion clearly shows that there is an active phase of soil organic N composed of biomass and ill-defined newly decomposed organic materials that is subject to rapid (1-2 year) degradation. This principle aids greatly in unlocking the puzzle posed by Heichel and Barnes (1984), who discuss the commonly observed finding that annual grain legumes such as soybeans or first-year alfalfa can contribute significantly to the N economy of the following cereal grain even though N budgets show convincingly that they remove more N from the soil than is fixed symbiotically (see also LaRue and Patterson 1981).

On tillage, the N-rich residues become part of the active phase. The MIT model also predicts accurately that the legume residue effect is short-lived (1-2 years) and may not be great (Ladd et al. 1983). If the annual legume crop is largely removed as hay, the net long-term effect may be degrading or at least no net gain in soil organic N.

Internal N cycle modeling concepts have advanced considerably recently. Most of the attention has been on cropped systems. With the exception of the Australian work, virtually no ^{15}N data exists to build on N cycling and availability in legume-based pasture or cut-and-carry systems. Research is needed to expand the data base. An active tri-national modeling group to develop conceptual and management models to improve efficiency of N use from legume residues should be convened.

Acknowledgement

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Discussion

Stern: Your soil biomass values: Can you put an absolute value on them?

Keeney: Yes, and they turn out quite reasonable, usually in the range of 50 to 200 kg ha^{-1}.

Ball: Data obtained from Ireland suggest that the best relationship is obtained from comparing last year's fixation with this year's N status.

Keeney: Yes, agreed. This paper was recently brought to my attention.

Field: We have been involved in modeling these systems, and the intermediate pool is mineral N. There are various estimates of this. A good estimate of mineralization is obtained from net change in the mineral N pool. We were unable to determine turnover of clover root and stolon material, and this has a large compensatory effect.

Keeney: We have tried to investigate some of the underground transfer systems. One is probably better off with simple models which look at a dynamic situation than with complicated chemical tests.

Steel: A Ruakura microbiologist has looked at biomass N/biomass C in microbes; this shows interesting seasonal changes. Are you aware of any United States data on this ratio?

Keeney: No, but it would be the best way to approach biomass dynamics.

Sheath: I want to put this OM biomass into perspective. New Zealand is lucky to have a system with a high supply of readily mineralizable N. This is in contrast to many overseas soils. Is there any way the manager can change these characteristics of soils to his advantage?

Keeney: Try and keep things in phase 2-3 of the pasture development, and, of course, use this mineralizable N for the efficient production of grain crops.

Nitrogen Recovery by Crops that Follow Legumes

G.H. Heichel[1]

Abstract

In legume-nonlegume crop sequences, the net recovery of legume N by the nonlegume varies with the quantity of legume residue returned to the soil, the content of legume N derived from symbiotic activity, and the availability of N from the decomposing legume for uptake by the nonlegume. The quantity of legume residue returned to the soil is a function of harvest management. The proportion of N in the residue that is derived from symbiosis depends upon legume species, management practices, environmental effects, and the availability of indigenous soil N to the legume. The availability of legume N to a subsequent nonlegume is affected by the C:N ratio of the residues, species factors influencing phytomass degradation by microflora, environmental factors, and soil properties. Use of ^{15}N methodologies suggests that 15% to 25% of the symbiotic N in a legume will be recovered by the first subsequent nonlegume crop, and perhaps another 4% by the second. The quantities of N recovered by the nonlegume are 8% to 22% of those estimated by equating the nonlegume yield response to legume incorporation to that from application of N fertilizer. The results exemplify the need for better understanding of the N contribution from forage legumes in cropping systems and for better methods of crediting the N value of legumes in agronomic recommendations for fertilization practices.

Introduction

Legumes have long been known to improve the yield of subsequent nonlegume crops (Pieters 1927). The role of dinitrogen (N_2) fixation by legumes as one factor in this yield improvement became known early in this century (Fred et al. 1932), although other factors contributing to a "rotation effect" have been implicated (Baldock et al. 1981, Heichel and Barnes 1984). Use of legumes as green manures in U.S. cropping systems reached a maximum about 1940, when an estimated 5.25 million ha were planted (Rogers and Giddens 1957). The knowledge that forage legumes were capable of fixing N_2 frequently fostered the belief that practically all legume nitrogen (N) was derived from the atmosphere, despite some pioneering evidence that soil N substituted for atmospheric N_2 in legume nutrition (Allos and Bartholomew 1959). Thus, the fertilizer value of forage legumes in U.S. agriculture was commonly based upon the N content of the phytomass incorporated as a green manure (Stickler et al. 1959, Schmid et al. 1959), without regard to the possible uptake and recycling of soil N by the legume. This interpretation still prevails in applied agronomic literature (for example, Martin and Touchton 1983).

The amount of N_2 fixed by a forage legume and subsequently made available to a nonlegume crop depends upon numerous environmental, edaphic, and management factors. The recent development of ^{15}N methodologies for determining the N budget of legumes and for tracing the nonlegume uptake of N from decomposing legume residues has provided new understanding of the contribution of legume N to a subsequent non-legume. This paper will develop and synthesize our present state of knowledge.

Sources of N for Legumes

Legumes derive N from two principal sources--the soil, through fertilizer application or mineralization of organic matter, and atmospheric N_2 by symbiotic fixation. Forage legumes grown on soil with the same initial N concentration in the profile derive different proportions of N from symbiosis (table 1). Birdsfoot trefoil (Lotus corniculatus L.) may have derived less N from symbiosis than the other forage legumes because of its lower productivity and lack of persistent nodules, which must be reestablished after each harvest. The proportion of N derived from symbiosis also varies with stage of growth, which may reflect the countervailing effects of soil N uptake by the plant and activity of the symbiotic system.

Legumes grown on soils with different initial soil N concentrations may also vary in proportion of N derived from symbiosis (table 1). These results exemplify the well-known principle that excess combined N in the soil solution suppresses nodule formation and nitrogenase activity of established nodules.

It is now clear that several factors influence the proportion of legume N derived from symbiosis and that soil N contribution to legume N content represents a temporary storage until it is recycled back to the soil N pool. The principles developed below will apply equally to the recovery of soil and symbiotic N contained in legumes. However, only recovery of symbiotic N by a subsequent crop represents a net substitution for fertilizer N unless, of course, the legume recovers soil N that would be permanently lost to leaching.

Legume N Return to Soils

In legume-nonlegume crop sequences, the amount of fertilizer N that can be replaced by legume N depends upon (a) the quantity of legume residue returned to the soil, (b) the content of symbiotically fixed N in the residues, and (c) the availability of the legume residue N to the succeeding nonlegume. The first two of these factors will be discussed here. The application of ^{15}N methodologies has allowed development of N budgets showing how crop N_2 fixation capability, N partitioning among organs, and crop management influence the return of N to the soil.

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Table 1 - Variation of N_2 fixation capacity with legume species, legume productivity, and initial soil N concentration; forage legume data adapted from Heichel et al. (1981); grain legume data from Vasilas (1981)

Species	Harvest 1	2	3	Mean	Dry Matter Yield
	(% N from symbiosis)				(kg/ha)
Forage Legumes					
Alfalfa[1]	49	81	58	63	7,645
Red clover[1]	51	79	65	65	6,995
Birdsfoot trefoil[1]	27	67	25	40	5,840
Harvest at grain maturity; grain legumes					
Soybean[2]		76			2,800
Soybean[3]		52			8,800

[1]Established in soil with 37 g/kg organic matter and an initial NO_3-N concentration of 12 mg/kg (0-15 cm depth).

[2]Established in soil with 18 g/kg organic matter and an initial NO_3-N concentration of 12 mg/kg (0-20 cm depth).

[3]Established in soil with 48 g/kg organic matter and an initial NO_3-N concentration of 31 mg/kg (0-20 cm depth).

Partitioning of N Sources, and Effects of Management

Nitrogen budgets of soybean (Glycine max L. Merr) developed from ^{15}N measurements exemplify the partitioning of symbiotically fixed N_2 in a crop with different amounts of symbiotic activity (table 2). Under Midwestern U.S. conditions, soybeans may obtain 40% of their N from symbiosis and 60% from the soil. When these crops are harvested for grain, soil N export may exceed symbiotic N return in the residue by 84 kg N/ha, which leads to a calculated soil N reduction. If the crop can be grown under conditions where it derives 90% of its N from symbiosis, symbiotic N return in the residue may exceed soil N export in grain by 24 kg N/ha. Clearly, there would be a net return of N to the soil by both types of crops if each were used without harvest as green manures.

Only part of the symbiotically fixed N_2 in a forage legume is typically returned to the soil for use by a succeeding crop. This is because a portion of the symbiotically-fixed N_2 is removed from the land when the legume is harvested, with the balance remaining in unharvested roots and crowns. The N available for incorporation into the soil depends upon the time of the season when incorporation occurs, and the proportion of the plant that is N-rich herbage compared with relatively N-poor crown and roots. The N budget in table 3 illustrates the net N return to the soil that is possible when alfalfa (Medicago sativa L.) is incorporated by either fall or late-summer plowing.

If two herbage harvests are taken, followed by herbage regrowth before plowing on October 20, the early season N deficit is nearly replaced by the late season N_2 fixation so that only an inconsequential loss of 5 kg N/ha occurred. In contrast, removal of one herbage harvest followed by plowdown of a lush regrowth on August 30 allowed a net input of 53 kg N/ha. Clearly, the benefit of growing a forage or grain legume before a subsequent nonlegume will be greatly influenced by how the legume is managed.

Estimation of Legume N Recovery by Nonlegumes

Legume Equivalence to Fertilizer N

A frequent agronomic approach to assessing the N-supplying capability of a legume preceding a nonlegume is to compare the yield of the nonlegume following the legume to that obtained from various levels of N fertilizer applied to the nonlegume following some reference nonlegume (Fribourg and Bartholomew 1956, Higgs et al. 1976). Forage legumes evaluated by this approach are interpreted to supply varying amounts of N to a subsequent crop during the first cropping season after plowdown of the legume (table 4). These values are likely overestimates of the contribution from symbiotic N owing to several confounding issues. First, the

Table 2 - Nitrogen budget of soybean illustrating the allocation of soil and symbiotic N among plant components and the net return of N to the soil with 40% and 90% of plant N from symbiosis (adapted from Heichel and Barnes 1984)

Crop component	Dry matter content (kg/ha)	Total reduced nitrogen content (kg/ha)	Content of symbiotic nitrogen (kg/ha)		Soil N export in grain (kg/ha)		Symbiotic N return in residue (kg/ha)		Loss (-) or gain (+) of nitrogen (kg/ha)	
			% N from symbiosis							
			40	90	40	90	40	90	40	90
Grain	2,358	170	68	153	102	17				
Residue[1]	3,845	45	18	41			18	41		
Total	6,203	215	86	194					(-)84	(+)24

[1]Pod walls, leaves, stems, roots, and nodules.

Table 3 - Nitrogen budget for seeding-year alfalfa illustrating the allocation of soil and symbiotic N among crop components and the net return of N to the soil with two plowing practices (adapted from Heichel et al. 1981)

Item	Harvest First (July 12)	Second (August 30)	Third (October 20)
Herbage yield (kg DM/ha)	3,503	3,054	1,156
Total reduced N yield (herbage and crown and roots) (kg N/ha)	118	127	59
Total N fixed (kg N/ha)	57	102	34
Herbage	52	74	22
Roots and crown	5	28	12
N from soil	61	25	25
Herbage	54	18	16
Roots and crown	7	7	9
Management Options			
Plow October 20			
N return/harvest (kg/ha)	-49	+10	+34
Cumulative N return (kg/ha)	-49	-39	- 5
Plow August 30			
N return/harvest (kg/ha)	-49	+102	
Cumulative N return (kg/ha)	-49	+ 53	

values in table 4 represent the response of the nonlegume crop to the N mineralized from the legume residue and do not distinguish between the N fixed by symbiosis and the turnover of soil-derived N that comprises the balance of the legume N. Acceptance of these results also requires the assumption that the sole cause of the non-legume yield response is the N from the legume. A third assumption is that the N in the fertilizer source and in the legume phytomass are equally available to the nonlegume. A fourth assumption is that the N supplying capacity of the soil is not altered by growth of the legume and incorporation of legume residues. A final problem in determining legume equivalence to fertilizer N is that the amount of legume N incorporated is seldom measured, so that quantitative estimates of the availability of legume N to the subsequent crop are precluded.

In experiments designed to obviate the latter deficiency, Fribourg and Bartholomew (1956) compared the relative efficiency of legume N recovery to that from NH_4NO_3. They found that an average of 34% of the N in freshly incorporated alfalfa and 10% of the N in similarly treated red clover herbage became available to corn (Zea mays L.) in the first subsequent year. In the second subsequent year, 7.5% of the alfalfa N and 3.5% of the red clover N became available to oats (Avena sativa L.).

In contrast to the approach of Fribourg and Bartholomew, Yaacob and Blair (1980b) grew Rhodesgrass (Chloris gayana L.) in pots containing the residues of one, three, or six crops of soybean or Siratro (Macroptillium atropurpureum L.), but they did not employ a reference treatment of inorganic N. Their approach overestimated the availability of legume N since the contribution of legume N was not separated from that of the soil. For example, the first crop of Rhodesgrass recovered 188% (soybean) or 150% (Siratro) of the amount of plant N added in the residues of one legume crop, indicating that the subsequent crop utilized the soil N as well as the added legume N. The first grass crop following three legume crops recovered 24% (soybean) or 32% (Siratro) of the amount of the added plant N, while the recoveries following six legume crops were 36% (soybean) and 67% (Siratro).

Legume N Availability to a Succeeding Crop Measured with ^{15}N

Use of ^{15}N methods has allowed more accurate estimates of legume N recovery by a succeeding crop (table 5). The pioneering experiments by Norman and Werkman (1943) revealed 25% recovery of the ^{15}N in decomposing soybean shoots during 11 weeks of subsequent soybean growth in pots. Yaacob and Blair (1980a) observed that the ^{15}N from decomposing Siratro leaves was more available to Rhodesgrass than that from decomposing soybean shoots. More ^{15}N was recovered from residues of either species applied to soil with 6 previous years of legume cropping than from soils with 1 or 3 years of previous legume cropping. Ladd et al. (1981) found that wheat grown for 8 months in the field on three soils amended to 10 cm with 38 to 57 kg N/ha from medic (Medicago littoralis L.) residues recovered on average 14% of the applied ^{15}N. In subsequent experiments, Ladd et al. (1983) observed that wheat plants grown for 8 months on three soils amended to 7.5 cm with 24 to 97 kg N/ha from medic residues recovered an average of 23% of the applied ^{15}N. A second crop of wheat recovered an additional 4%, on average, of the residue N. Vallis (1983) found that ^{15}N from decomposing Siratro was more available during the subsequent year of Rhodesgrass cropping

Table 4 - Fertilizer N value of various forage legumes managed as green manures or as hay, plowed under in the fall and planted to corn the subsequent year

Legume	Fertilizer N value (kg N/ha)	Reference
Alfalfa (winterdormant)	9[1]	Stickler et al. 1959
	45-94	Schmid et al. 1959
	135-168[1]	Schmid and Otto 1967
	168	Higgs et al. 1976
	112-180	Voss and Shrader 1979
Alfalfa (nonwinterdormant)	56[1]	Stickler et al. 1959
Birdsfoot trefoil	94	Schmid et al. 1959
Ladino clover	13[1]	Stickler et al. 1959
Red clover	25[1]	Stickler et al. 1959
	94	Schmid et al. 1959
	135-168[1]	Schmid and Otto 1967
Sweet clover	112[1]	Sticker et al. 1959
	135-168[1]	Schmid and Otto 1967

[1]Legume managed as green manure (no legume harvest). All others managed as hay with various cutting schedules.

Table 5 - Characteristics of legume residues and recovery of N contained in various legume species by the first and second subsequent crops

Residue (application method)	Residue N (%)	Residue C:N	Residue ^{15}N (% a.e.)	Residue Addition (kg N/ha)	Soil total N (%)	Assay Crop Species	Assay Crop Growth Period	Legume N Recovery (% of addition) Crop 1	Legume N Recovery (% of addition) Crop 2	Reference
Soybean tops, less grain (all soil in pot)	2.15	19.5	0.317	201		Soybean (un-inoculated).	11 weeks	25.3		Norman and Werkman (1943)
Soybean tops, less grain (all soil in pot)	1.48	28.4	.388	221	0.04 .04 .09	Rhodesgrass (tops)	6 wk; 6 wk	7.0 8.2 10.1	3.8 4.1 3.9	Yaacob and Blair (1980b)
Siratro leaves (all soil in pot)	2.61	16.1	.343	391	.05 .06 .11	Rhodesgrass (tops)	6 wk; 6 wk	9.2 32.6 41.5	2.0 5.5 10.3	
Medic, tops and roots, (0-10 cm in field)		14.9	3.59	38 57 57	.09 .09 .09	Wheat (whole plant)	8 months	13.8 17.3 10.9		Ladd et al. (1981)
Medic, tops and roots, (0-7.5 cm in field)		11.1	2.68	48	.17	Wheat (whole plant)	8 months	27.8		Ladd et al. (1983)
						Wheat (tops)	8 months		4.8	
				48	.09	Wheat (whole plant)	8 months	20.2		
				24 48 97	.17	Wheat (tops)	8 mon, 8 mon	22.4 24.9 21.1	4.3 4.1 3.3	
Siratro leaves, (soil surface, field)	1.35	31.0	4.92	67	.33	Rhodesgrass (whole plant)	1 yr, 2 yr	12.8	16.6	Vallis (1983)
Siratro Stems, (soil surface, field)	.49	85.7	5.12	67	.33	Rhodesgrass (whole plant)	1 yr, 2 yr	9.7	14.0	
Desmodium leaves, (soil surface, field)	1.79	23.5	4.94	67	.33	Rhodesgrass (whole plant)	1 yr, 2 yr	9.8	10.7	
Desmodium stems, (soil surface, field)	.58	72.4	5.16	67	.33	Rhodesgrass (whole plant)	1 yr, 2 yr	6.8	11.6	

than was ^{15}N from decomposing Desmodium. For both species, ^{15}N from decomposing leaves was more available than that from decomposing stems. After 1 year of Rhodesgrass cropping, 7% (Desmodium) to 11% (Siratro) of the ^{15}N in the legume was recovered. In the second year of cropping, an additional 11% (Desmodium) to 15% (Siratro) of the ^{15}N in the legume was recovered by the grass.

Synthesis and Contrasts

The emerging knowledge of legume N_2 fixation and the availability of legume N to a subsequent crop is sufficient to support a model of the net (exclusive of recycled soil N) recovery of legume N by a subsequent crop (fig. 1). The evidence reviewed above suggests that 60% to 85% of N in legumes may be derived from the atmosphere and that 15% to 25% of the N in legume residues may be available to the

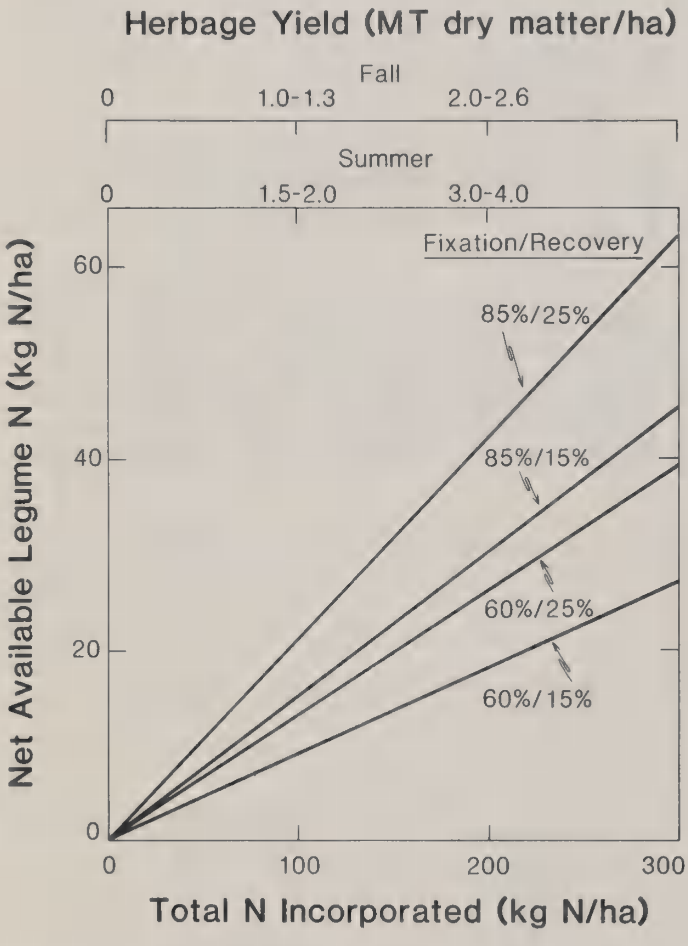

Figure 1--Hypothetical representation of the net recovery of N from incorporated forage legume residues. Values of net N recovery by a subsequent nonlegume are calculated for two cases of legume N_2 fixation capacity (60% and 85% N from symbiosis) and two efficiencies of legume N recovery by the nonlegume (15% and 25%). Dry matter yields only approximate crop N content and are intended to illustrate the quantities of crop N available for incorporation from summer or fall plowdown of forage legumes managed for 2-4 cuts of hay in the North Central United States. Use summer yield values for forage legumes grown as green manures without harvest.

first subsequent crop. Using Midwestern U.S. forage yields as examples, the incorporation during the summer of a forage legume crop yielding 3 to 4 metric tons dry herbage/ha (about 200 kg N/ha in shoots, crowns, and roots) might lead to the recovery in the first year of 18 to 42 kg/ha of N originally derived from legume fixation. Incorporation of a crop yielding 1 to 1.3 metric tons dry herbage/ha (about 100 kg N/ha in shoots, crowns, and roots) in the fall might lead to the recovery of 9 to 21 kg/ha of N originally derived from legume fixation.

By adjusting values of the total N content of forage legume crops to reflect the experimental measurements of net gain of N_2 through fixation, and experimental measurements of legume N availability to a subsequent crop, three examples can be advanced for comparison with results in table 4. Management of alfalfa or red clover as a green manure in the North Central United States might be expected to allow dry matter yields of 3 to 4 metric tons/ha, or total N yields of about 200 kg N/ha, in the fall of the seeding year. The model in figure 1 suggests that an average of 30 kg N/ha from symbiotic fixation would be available to a subsequent nonlegume. The most recent results in table 4 credit alfalfa and red clover managed as green manures with a yield response equivalent to application of 135 to 168 kg N/ha of manufactured fertilizer, fourfold to fivefold more N than values predicted from experimental measurement.

Management of alfalfa or red clover as hay might result in a second harvest during summer of 2 metric tons/ha. If this crop instead was plowed down, a total N yield of 100 kg N/ha might be incorporated. The model in figure 1 suggests that an average of 15 kg N/ha from symbiotic N_2 fixation would be available to a subsequent nonlegume. Similar average amounts of N would be available from incorporation of a 1 to 1.3 metric tons herbage/ha crop in the fall. The most recent results cited in Table 4 credit alfalfa or red clover managed as hay with a yield response equivalent to application of 94 to 180 kg N/ha of manufactured fertilizer, sixfold to twelvefold more N than the values predicted from experimental measurement.

Future Research

The marked contrast between ^{15}N and fertilizer N equivalency methods of estimating the recovery of legume N by subsequent crops suggests the need for a thorough reexamination of the assumptions underlying the latter methodology. It is possible forage legumes are being improperly credited with more N than they are actually contributing to the soil-plant system. Recent analyses suggesting that the maximum N contribution is about 75% of the yield enhancement attributable to planting corn after alfalfa (Baldock et al. 1981) and that corn yields following wheat equal those of corn following wheat underseeded with alfalfa (Langer and Randall 1981) support this position. Pending further experimentation, the available data suggest that only 25% of the symbiotically fixed N contained in a legume will be recovered by the first subsequent nonlegume crop, and another 4% by the second crop. These values will underestimate legume N

availability if the soil N is enriched during legume growth by N from exudates, leachates, or products of phytomass decomposition. Further application of ^{15}N methodologies will greatly aid the understanding of the role of legume N_2 fixation in the N cycle of crop rotations.

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Discussion

Runge: Are the other elements important to understanding the C:N ratio?

Heichel: Apparently not too important, but more work is needed.

Marten: There should be an increase in N storage through breeding. How much N stored will be obtained by the corn crop?

Heichel: Probably an increase by 10%. There are high coefficients of variation, and there is likely to be little chance of measuring this in practice.

Rumbaugh: What are the reasons for differences between (a) cuts, 1, 2, and 3, and (b) for differences between legume species?

Heichel: (a) Trefoil. When harvested, nodules deteriorate immediately, which is different from other species. This may be one reason for the lower proportion of N from symbiosis of this species compared with red clover and alfalfa. (b) Seasonal pattern is responsible. Data were obtained in an establishment year. Soil NO_3 was 12 ppm, and the low proportion of N fixed reflects dependence on soil N until the first harvest. Harvests 2 and 3 reflect the running down of soil NO_3. More data are required on mineralization through time. The decline may also be because of plants entering dormancy.

Knight: Would your results extrapolate to other legumes such as crimson clover and vetch, i.e., the disappointingly low level of fixed-N being transferred to the following crop?

Heichel: Don't know. I agree that the answer would be important to the Southeastern United States farmers.

Vallis: I think part of the legume effect can be attributed to "stoking up" of the N cycle in soil. There appears to be an improvement in mineralization with additions of subsequent legume material. For example, a third addition released more net minerals than a first addition in the work of Yaacob and Blair.

Minson: Are you recommending longer experiments?

Vallis: Yes.

UTILIZATION OF FORAGE LEGUMES IN RUMINANT LIVESTOCK PRODUCTION

Nutritional Value of Tropical Legumes in Grazing and Feeding Systems

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Abstract

Three aspects of the nutritional value of tropical legumes are reviewed: chemical composition, energy value, and voluntary intake. Tropical legumes generally contain high levels of protein and all minerals except sodium. The digestibility of tropical legumes is low and similar to that of tropical grasses, but the voluntary intakes are higher than the grasses due to the shorter time they are retained in the rumen. Some legumes are unpalatable in the spring, and when grazed the stem of coarse legumes is generally rejected. Future work should concentrate on breeding legumes of higher digestibility and possibly higher sodium content and on studies designed to determine the maximum nutritional benefits that can be achieved from the dietary interaction of tropical legumes and grasses.

Introduction

Legumes can improve the quality of the diet of ruminants in three ways: by increasing the protein content of grasses grown in association with the legume (Jones et al. 1967), by increasing the intake of energy and protein by animals, and by increasing the length of time that green forage is available to animals. This review considers the chemical composition, energy value, and voluntary intake of tropical legumes.

Chemical Composition

Essential Nutrients

Animal production from tropical legumes will be limited if they contain insufficient mineral elements or protein and if these nutrients cannot be obtained from other sources, i.e., other plant species, supplements, drinking water, soil or body reserves. The potential of tropical legumes to supply these essential nutrients varies with the element and between legume species, stage of growth, and other variables. Each nutrient will be considered separately.

Phosphorus. Tropical legumes contain, on average, 0.26% phosphorus (P), which is slightly higher than for tropical grasses (0.22%, Norton 1982). There is considerable variation in the P content, with 7% of all samples containing less than the 0.12% considered adequate for growing cattle fed a tropical legume (Little 1980). There is variation in the P levels of *Stylosanthes* species and between forage harvested in the summer and winter (Gardener et al. 1982). Some *Stylosanthes* species have a low requirement for P, and although they grow well on P deficient soils they often contain less P than is required for maximum animal production (Norton 1982).

Depending on local economic factors, P deficiency in the animal may be overcome by either P supplementation or the application of P fertilizer. With cattle fed *S. humilis* containing 0.07% P, a P supplement increased voluntary intake by 15% and liveweight gain from 0.13 to 0.38 kg per day (Little 1968). A similar increase was found with sheep fed *S. humilis* containing 0.08% P (Playne 1969). The application of 377 kg ha^{-1} $year^{-1}$ superphosphate to a *S. humilis*/grass pasture increased the mean P content of the legume from 0.10% to 0.14% (Ritson et al. 1971). Larger increases were reported by Shaw (1978), who increased the mean P level of grazed *S. humilis* from 0.11% to 0.17% by applying 250 kg ha^{-1} $year^{-1}$ superphosphate. However, in other studies, only small increases in P content have been reported following the application of superphosphate to *Desmodium intortum* (0.22% to 0.26%, Bryan and Evans 1973), *S. guianensis* (0.17% to 0.19%, Eng et al. 1978), and *Centrosema pubescens* (0.22% to 0.24%, Eng et al. 1978).

Calcium. The level of calcium (Ca) in tropical legumes is generally higher than in grasses, and it is usually well above the quantities required by grazing ruminants (Minson 1977). For 154 samples of tropical legumes, the mean concentration of Ca was 1.21% compared with 0.40% in tropical grasses and 1.86% for temperate legumes (Norton 1982).

Magnesium. Magnesium (Mg) levels in tropical legumes are generally high compared with those in grasses and generally adequate for ruminants (Minson 1977). Mean concentration of Mg in 48 samples of tropical legumes was 0.40% compared with 0.29% in temperate legumes (Norton 1982). No cases of hypo-magnesaemia have been reported for cattle grazing tropical pastures (Minson and Norton 1982).

Sodium. The sodium (Na) content of most tropical legumes is low to very low (Minson 1977). Of all values reported in the literature, 62% contained less than 0.05% Na (Norton 1982), the minimum dietary Na level recommended for any form of ruminant production (Agricultural Research Council 1980). This problem is illustrated by the low mean value of 0.07% for all tropical legume samples compared with mean values of 0.19, 0.23, and 0.26% for temperate legumes, temperate grasses, and tropical grasses respectively (Norton 1982). Feeding a Na supplement to cattle grazing a *Stylosanthes*/grass pasture has increased beef production from 0.12 to 0.51 kg d^{-1} (W.H. Winter, personal communication).

Copper. Low levels of copper (Cu) have been reported by Andrew and Thorne (1962) in *Centrosema pubescens* (2.0-5.9 ppm); *Desmodium uncinatum* (3.0-5.1 ppm); *Indigofera spicata* (1.8-4.8 ppm); *Macroptilium lathyroides* (1.7-3.8 ppm); and *Stylosanthes guianensis* (2.4-4.4 ppm). All these values are below the 8-20 ppm recommended by the Agricultural Research Council (1980), who assumed that only 4% of the Cu present in the diet was absorbed. Norton (1982) reported a mean value of 10 ppm for a range of tropical legumes cited in the

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literature, while a mean of 16 ppm has been reported for leaf and stem fractions of Lablab purpureus (Hendricksen and Minson 1980). There appears to be no reports of cattle grazing tropical legumes responding to copper supplements.

Zinc. Zinc (Zn) levels have been reported for only a few tropical legumes. Norton (1982) reported a mean concentration of 42 ppm for seven samples, a value higher than the 12-35 ppm recommended by the Agricultural Research Council (1980) for cattle. In the tropical legumes Lablab purpureus, the leaves contained slightly more Zn than the stems, 34 versus 27 ppm (Hendricksen 1981).

Cobalt. Only three values for cobalt (Co) in tropical legumes have been published (Norton 1982). The mean of these samples was 0.07 ppm and below the 0.11 ppm recommended by the Agricultural Research Council (1980). Some of these samples were collected from legumes grown on cobalt-deficient soils so they do not represent the normal levels of Co in tropical legumes. Cobalt supplementation of cattle grazing tropical legume grass pastures with low levels of cobalt has increased growth rate (Mannetje et al. 1976, Winter et al. 1977).

Protein. Tropical legumes have a high crude protein (CP) content with a mean of 16.5% for a wide range of samples (Minson 1976). Values vary from 6% to 30% CP, but few contain less than 9% CP, and only 10% of all samples studied contain less than 12% CP, a level adequate for beef production and low levels of milk production (Agricultural Research Council 1980).

The CP content of tropical legumes declines slowly over time, and even when mature, tropical legumes in general contain more than 9% CP. They can act as protein supplements to mature tropical grasses, which are frequently deficient in protein (Minson 1976), leading to an increase in intake of the grass (Minson and Milford 1967).

The leaves of tropical legumes contain more CP than the stems. In Lablab purpureus, the leaves contained 23% compared with 17% CP in the stem fraction (Hendricksen and Minson 1980, Hendricksen et al. 1981). The solubility of the CP in the leaves of tropical legumes is lower than in the stem (mean 24% vs 42%, Aii and Stobbs 1980). There are also large differences in solubility of the CP between legumes species. Low solubilities were found in Desmodium species, apparently due to the high tannin content (McLeod 1974, Ford 1978), but there is no direct evidence that this leads to any increase in animal production.

The apparent digestibility of the CP in tropical legumes varies considerably. Most of this variation is positively associated with the level of CP. The quantity of CP apparently digested per 100 units of feed dry matter (DCP) is closely related to the CP% of the dry matter by a relationship similar to that found in grasses.

Legume DCP = 0.93 CP-3.99 RSD $\pm$ 1.17 r = 0.96

Grass DCP = 0.90 CP-3.25 RSD $\pm$ 0.84 r = 0.98

Energy Value

Gross Energy

The gross energy concentration in the dry matter of tropical legumes appears to be similar to that of temperate legumes and all grasses: Desmodium uncinatum, 19.2 MJ/kg (Graham 1967); Macroptilium atropurpureum cv. Siratro, 18.4 MJ/kg (Minson and Milford 1966); and Vigna sinensis, 18.6 MJ/kg (McDowell et al. 1974).

Digestibility

The proportion of the energy digested is closely related to the more readily measured dry matter digestibility (DMD) which for tropical legumes varies from 36.0 to 69.3 with a mean of 54.0% (Minson 1977). These low values are similar to those reported for tropical grasses (Minson and McLeod 1970). The DMD of tropical legumes is only 4% lower than temperate legumes (Minson and Wilson 1980). This is in contrast to tropical grasses which are 13% lower than temperate grasses.

The DMD of tropical legumes declines as they mature but at a rate generally less than is found with tropical grasses. The edible portion of browse legumes shows little seasonal change (McLeod 1973, Bamualim et al. 1982). This decline in digestibility is associated with an increase in the level of crude fibre (CF) (Minson 1977).

DMD = 84.5 - 0.94 CF r = 0.79 RSD = $\pm$ 4.1

Animals selectively graze the leaf fraction (Zemmelink 1980), and legume leaves are 0.4% to 8.7% higher in digestibility than the stem fraction (Jones 1969, Hendricksen et al. 1981).

Metabolisable Energy

The only published value for metabolisable energy (ME) of tropical legumes was obtained in a calorimetric study with Desmodium uncinatum. It contained 6.53 MJ ME/kg dry matter of ME with a conversion efficiency of DE to ME of 0.81 (Graham 1967). This conversion value is similar to that found with temperate forages.

Net Energy

The net energy (NE) content has been published for only one tropical legume, a sample of Desmodium uncinatum. When fed to sheep, the NE at maintenance was 4.2 MJ/kg dry matter with a net availability of ME for maintenance of 65% (Graham 1967).

Voluntary Intake

The quantity of dry matter eaten by ruminants is the most important single factor controlling production. Unless the legume is eaten in large quantities, production will be low due to a low intake of digestible energy, no matter how high the digestibility. The voluntary intake by ruminants has been measured for tropical legumes cut and fed in pens and for grazed forage in the field. The intake in pens will be considered first since it is in pen studies that many of the factors controlling

intake have been identified. When tropical legumes are grazed, the factors that control intake in pens will still operate, but there are additional factors that limit intake (i.e., selective grazing, breaking strain, etc.).

Intake in Pens

The voluntary intake by sheep of tropical legumes varies from 17.3 g/kg $W^{0.75}$ (W = body weight) for Crotalaria lanceolata (Milford 1967) to 90.6 g/kg $W^{0.75}$ for leaf of Lablab purpureus (Hendricksen et al. 1981). When compared at the same dry matter digestibility, the voluntary intake of legumes is 28% higher than that of the grasses (Thornton and Minson 1973), a difference attributed to the shorter time they are retained in the rumen and high dry matter percentage of the rumen contents. Subsequent work has shown that with legume diets, water passes more rapidly through the rumen (Poppi et al. 1981, Hendricksen et al. 1981).

In a comparison of separated leaf and stem of Lablab purpureus, cattle and sheep ate 77% and 73% more leaf than stem, apparently because a smaller proportion of the large particle (>1 mm) in the stem fraction was broken down during eating and the stem fraction stayed a longer time in the rumen (Hendricksen et al. 1981). Zemmelink (1980) has also shown that the intake of a range of tropical legumes can be increased by feeding excess forage and allowing the animal to select the leaf fraction.

Intake with Grazing Animals

The only published intake data for cattle grazing pure tropical legume swards is for Lablab purpureus over periods of 14 days (Hendricksen and Minson 1980). The daily intake decreased from 11.5 kg $head^{-1}$ during the first two days to 2.8 kg $head^{-1}$ after 12 days of grazing. This decrease in intake was associated with a decrease in bite size. Intake was unrelated to number of eating bites (r^2 = 0.02) or grazing time (r^2 = 0.004). This decrease in intake and bite size was related to the quantity of leaf on offer; only 300 kg ha^{-1} remained at the end of the 12-day grazing period compared with 2500 kg ha^{-1} of stem. The cattle never ate more than 1.5 kg d^{-1} of stem, possibly because of the high shear strength of the stem. Even stronger selection for leaf and rejection of stem occurs in the shrub legumes and in tree legumes such as Leucaena leucocephala.

Selective Grazing

In swards containing more than one plant species, animals often exhibit a preference for or against the legume component. It has long been recognised that cattle completely reject some legumes and eat little if any Stylosanthes species in the spring. Recently it has been found that preference for this legume may be changed by applying superphosphate (McLean et al. 1981). Marked seasonal changes in preference have also been reported for Macroptilium atropurpureum (Stobbs 1977).

Future Work

The tropical legumes are an excellent source of nutrients when compared with the tropical grasses, and their presence in pasture usually leads to increases in production per animal (Davison and Cowan 1978). The main nutritional problems with legumes are their generally low digestibility and sodium content. Both problems might be reduced by plant selection or breeding, although feeding a mineral supplement or including a high sodium grass in the pasture may be a more economic method of overcoming the sodium deficiency. Legumes have a higher level of protein and minerals than most grasses, and when grown in mixed swards the legumes can act as a supplement to tropical grasses. Although this supplementary action is widely recognised, there is a need to delineate the factors controlling the level of benefits that can be achieved with special emphasis on voluntary intake, digestibility and net energy content of grass/legume mixtures.

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Discussion

Barry: It appears that the proportion of speargrass in the bolus is much greater than legume. Why is this preference shown by stock?

Minson: The palatability of grass and legume changes throughout the year, and the proportion of legume in the bolus will alter accordingly.

Barry: What is the nitrogen content of the leaf of the tropical legume and speargrass?

Minson: Immature legume averages 3.5% and the speargrass, 2.0%.

Brougham: Tropical legumes show a lot of interesting attributes, but to be useful a legume must be maintained in the pasture. The main effort has been on trailing legumes. Bunch legumes might persist better. What is their value?

Minson: The data presented apply to all tropical legumes. A high stem content will affect intake.

Jorgensen: Is there information on the availability of nutrient elements from tropical legumes and on the effect of maturity?

Minson: There are no Australian data from tropical legumes.

Marten: What is the range of nutritive values in the leaf and stem of the tropical legume?

Minson: These values follow the expected trends of greater variation in the stem than in the leaf.

Syers: The paper did not discuss sulfur, which can be deficient in tropical soils.

Minson: There are very few data on sulfur in tropical legumes.

Burns: Has there been any work investigating the proportion of legumes needed in the pasture for animal nutrition?

Minson: No.

Barnes: How many data points are involved in your graphs on tropical legumes?

Minson: For nitrogen--800 observations; for digestibility--170 observations.

Jorgensen: Is there research on the effect of the lignin/fiber interaction on rate of flow through the rumen for tropical legumes?

Minson: Yes. Past work focused on digestibility. Our present interest is in the rate of breakdown to the 1 mm particle size, which is an essential element in speed of passage through the rumen. The multidisciplinary group at the Cunningham lab is interested in the importance of the various phases of breakdown and the histological and chemical factors conferring resistance to breakdown of the indigestible fraction.

Utilization of Forage Legumes in Ruminant Livestock Production in New Zealand

David A. Clark and M.J. Ulyatt[1]

Abstract

White clover and most other legumes are grazed in mixed swards in New Zealand. The short, dense grass-legume swards make it difficult for grazing sheep to improve diet quality by selecting for legumes. The presentation of clover as relatively pure strips would allow a significant increase in the legume content of the diets. Goats actively reject white clover and selectively remove grass, so goats or mixed sheep-goat grazing improve the competitive balance in favour of legumes.

White clover is markedly superior to grass species in feeding value and has an additive effect when fed with grasses. It is also consistently superior to other legumes, mainly because of a better soluble:structural carbohydrate ratio. Voluntary food intake of sheep on white clover is 9%-28% higher than ryegrass at the same OM digestibility. Rumen retention times are 25% less on white clover and chewing breakdown more rapid. At the same OM intake, 17% more N reaches the duodenum because of the 14% higher N content of white clover. When coupled with higher voluntary food intake, 34%-51% more N reaches the duodenum, which is the major reason for differences in feeding value between white clover and perennial ryegrass. If this improved feeding value is to contribute to animal production, selective herbicides, legume oversowing, and cattle and goat grazing need to be more critically evaluated for farm use.

The Use of Legumes as Livestock Feed

Introduction

In New Zealand, most legumes contribute to animal production as a component of mixed grass-legume swards. White clover (Trifolium repens L.) is the predominant pastoral legume. It is sown in most seed mixtures, and its contribution to the dry matter (DM) available in N.Z. pastures ranges from 2% to 39% with a mean of 27% (Hoglund et al. 1979). White clover contribution is above average in areas of low available soil nitrogen (N) and good rainfall, providing soil phosphorus is adequate. It is below average in areas of low soil phosphorus and low rainfall. Other legumes make an important but largely undocumented contribution to animal nutrition from pasture: e.g., red clover (Trifolium pratense L.), suckling clover (T. dubium L.), subterranean clover (T. subterraneum L.), alsike clover (T. hybridum L.), medics (Medicago spp.) and Lotus spp.

Some special-purpose legume swards are produced in New Zealand. Lucerne (Medicago sativa L.) predominates, occupying approximately 116,000 ha, while white clover, red clover, and Lotus pedunculatus Cav. seed crops are sometimes available for post-harvest grazing. Lucerne is capable of producing high DM yields of excellent feeding value in drier areas. The use of lucerne on dairy farms in the central volcanic plateau of the North Island has increased markedly over the past 10 years. The average dairy farm in the region has 25% of its area sown in lucerne, which provides high quality feed from October to April and has been responsible for increased per cow and per hectare production. There is less evidence for successful use of lucerne by beef farmers. Lucerne is used in some drier areas of New Zealand, such as Canterbury and the central plateau of the North Island, to improve sheep nutrition. Farm comparisons suggest that good management will result in: an extra 5-8 ewes/ha carried annually; ewes 3-4 kg heavier at weaning; 100% increase in summer carrying capacity; and 10%-50% higher lamb growth rates from October to April (Mace 1980). In addition, early weaning of lambs is more successful on lucerne than pasture (Rattray et al. 1976), although problems have been caused by the condition, "redgut," in Canterbury (Jagusch et al. 1976). Fertility problems caused by coumestans of fungal origin can arise from grazing infested lucerne prior to mating (Smith et al. 1980). However, these problems can be avoided by deferring grazing lucerne for two weeks before mating.

Diet Selection

White clover and, to less extent red clover, are the main legumes associated with N.Z. dairy pastures. There is little information on the diet selected by grazing beef or dairy cattle. However, on many of our dairy farms pasture utilization at each grazing is intensive, which suggests that legumes should contribute to the diet in proportion to their sward content. If this occurs, the marked seasonal variation in legume growth (Brougham 1962) will lead to similar changes in diet content.

White clover is also the main legume sown on N.Z. hill country. For sheep, diet selection has been measured with both pre- and post-grazing sward cuts, and more directly with oesophageal fistulated sheep. This work showed that sheep preferred green leaf material to dead matter (fig. 1), but did not selectively graze the legume component.

Recent work (D.A. Clark and P.S. Harris, unpublished data) examined the effect of horizontal distribution and content of white clover on diet selection. White clover content varied from 1% to 90%. In swards of normal spatial distribution, clover was eaten in proportion to its presence in the sward. When 'strips' containing approximately 80% clover were offered together with pure grass 'strips' there was some selection of white clover (fig. 2). Milne et al. (1982) created white clover swards that differed in their vertical distribution and recorded selection for white clover in the taller, less dense swards. In reviewing the subject of selective defoliation, Curll (1982) noted that clover selection decreased when herbage mass decreased below 1,000 kg DM/ha.

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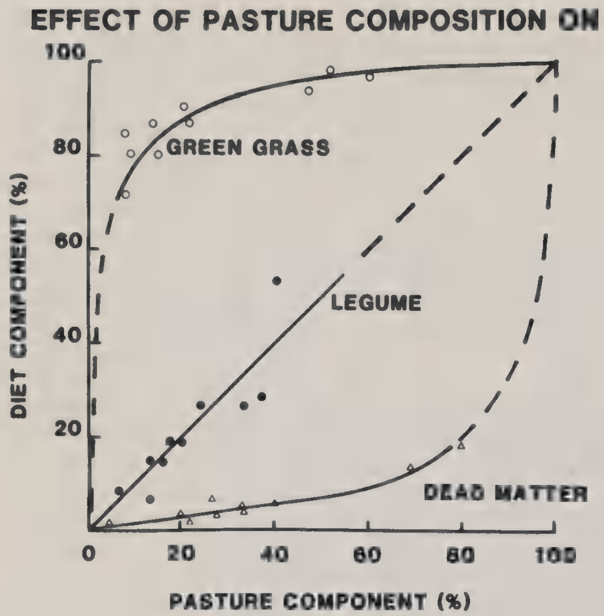

Figure 1--The relationship between diet and sward composition (%) for green leaf (0), dead matter (Δ) and legume (●) in intensively utilised pastures (Clark et al. 1982a).

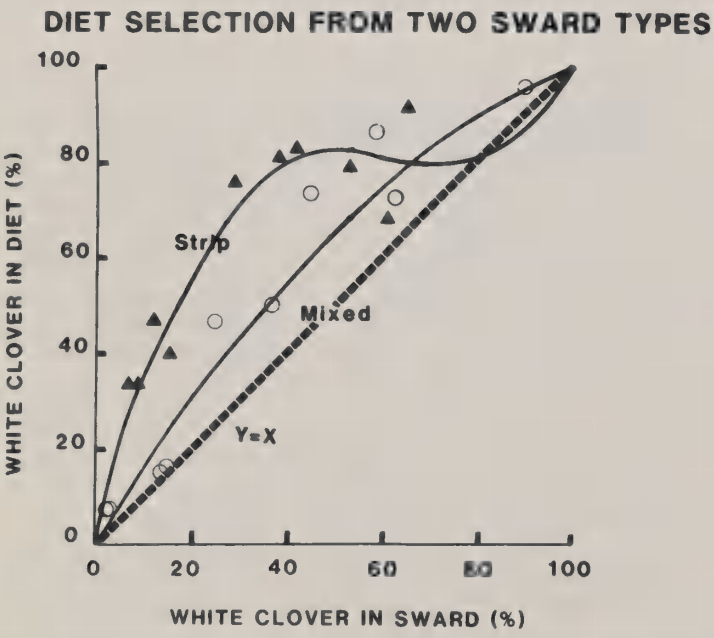

Figure 2--The relationship between white clover in the diet and the sward from 'mixed' (0 ——— 0) and 'strip' (▲ — — — ▲) swards.

D.A. Clark (unpublished data) has examined diet selection under rotational grazing and set stocking with sheep in a 2-year study on well-utilized hill country pastures. White clover selection varied with the seasonal change in its content in the sward (fig. 3) and was not significantly altered by grazing management. White clover contribution was generally small in these semi-developed hill pastures. This information suggests that for much of the year legumes are a relatively minor contributor to the animal's nutrition.

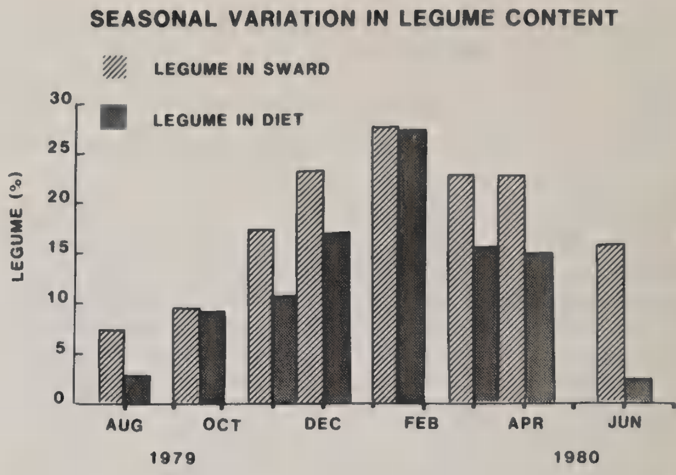

Figure 3--Seasonal variation in the sward and diet content (%) of white clover under set-stocked and rotational grazing management in moist hill country.

Goats have recently been shown to have diet selection characteristics that have important implications for N.Z. hill country agriculture. When goats and sheep graze a mixed sward community of white clover, grass, and the shrub legume, gorse (Ulex europaeus), goats reject white clover and consume grass and gorse (fig. 4). This rejection continues when gorse has been virtually eliminated. The rejection of white clover and removal of grass leads to increased clover yield where goats form the major grazing species (table 1).

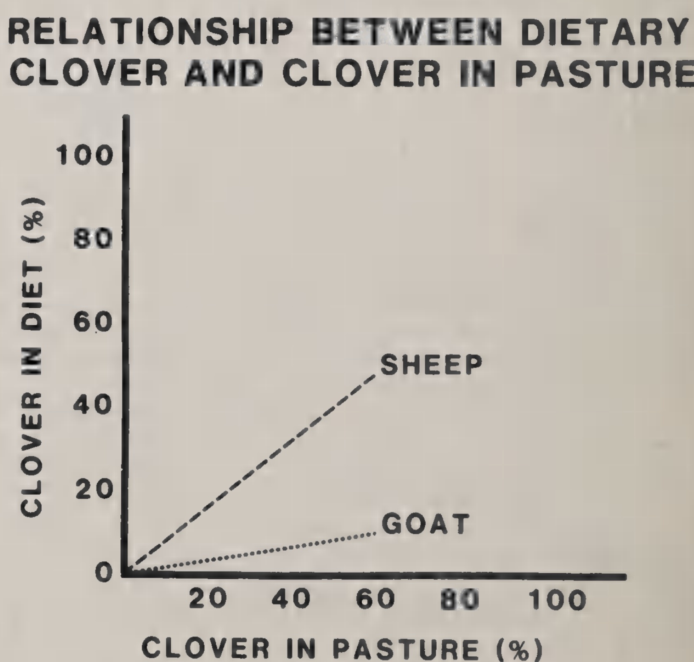

Figure 4.--The relationship between legume (%) in the diet (Y) and in the sward (X) for sheep and goats.
Sheep: $Y = -3.1(\pm 1.8) + 0.90(\pm 0.08)\ X$; $r=0.63 (P<0.001)$; $n=168$
Goats: $Y = 1.2(\pm 0.87) + 0.07(\pm 0.04)\ X$; $r=0.15$ ns; $n=135$
(Clark et al. 1982b).

Table 1 - Summer botanical composition (%) of hill country slopes (13°-25°) on pasture grazed by 100% sheep, 66% goats and 34% sheep, and 100% goats (Clark et al. 1984)

Pasture species	Sheep 100%	Goat 66%	Goat 100%
White clover	1	10	26
Perennial ryegrass (Lolium perenne)	21	2	5
Browntop (Agrostis spp.)	33	24	5
Yorkshire fog (Holcus lanatus)	20	18	41
Poa spp.	8	7	16
Other species	17	39	7

The Feeding Value of Legumes

There is far more information from New Zealand on the feeding value (animal performance response) of white clover than any other legume; a fact that reflects its agronomic importance in this country. White clover is markedly superior to grass species in feeding value, with sheep liveweight gains often approaching double those attained on perennial ryegrass (Ulyatt 1981). The addition of white clover to grasses has consistently improved the feeding value compared with grasses alone, the response being proportional to the amount of clover in the pasture (Rae et al. 1963, Rattray and Joyce 1974). While there is less information available on the comparative feeding value of other legumes, results from N.Z. work indicate that at the pre-flowering stage, white clover is consistently superior to lucerne, red clover, *Lotus* spp., and sainfoin (*Onobrychis viciifolia* Scop.), which in turn are superior to perennial grasses (Ulyatt 1981). Pasture allowance trials have confirmed these results (Jagusch et al. 1979) and have shown that the high growth rates required for both replacement and prime lambs are achieved at lower pasture allowances on legume compared with grass swards.

Why are Legumes of Higher Feeding Value?

Voluntary Food Intake

The primary determinant of feeding value is voluntary food intake. Experiments, both indoors and in the field, in which white clover and perennial ryegrass were fed *ad lib.* at the same digestibility have demonstrated 9% to 28% higher intakes of white clover in sheep (Joyce and Newth 1967, Rattray and Joyce 1969, Ulyatt 1971) and up to 43% in grazing cattle (M.J. Ulyatt, D.E. Beever, and D.J. Thomson, unpublished data).

Comparisons between legume species in voluntary intake have also been published (Ulyatt et al. 1977) and show that differences exist: higher intakes were achieved with red clover, sainfoin, and *Lotus corniculatus* than with lucerne. Stage of maturity of the plant has a large influence, as the digestibility of all legumes, and thus voluntary intake declines as the plant matures. This decline is caused by an increase in the stem/leaf ratio with maturity, and a concurrent increase in structural carbohydrate and decrease in both soluble carbohydrate and protein (Bailey et al. 1970). This decline in digestibility is more severe with the erect forage species, such as red clover and lucerne (Davies et al. 1966). White clover maintains a higher digestibility throughout its growth because the harvestable material is largely leaves and petioles, which continually turn over as aged material is replaced by new growth.

The reason for the generally higher intake of legumes than grasses can be seen by examining white clover and perennial ryegrass. At the same digestibility, the retention time for white clover residues in the rumen is 12 hours while that for perennial ryegrass is 16 hours (G. Moseley and D. Dellow, unpublished data). White clover is broken down by chewing and fermentation more rapidly than perennial ryegrass because white clover contains more readily fermentable substrate and less poorly digested, fibrous material (Ulyatt et al. 1977). This allows the animal to eat more clover. Differences within species with advancing maturity can be explained in the same way.

Nutritive Value

Legumes generally have a higher nutritive value (animal performance per unit of food intake) than grasses. Again, most of our understanding comes from research comparing white clover with perennial ryegrass. The superiority of white clover is related to more protein reaching the duodenum, and thus available for absorption, or conversely, because insufficient protein reaches the duodenum in sheep fed perennial ryegrass. Comparisons of duodenal N flow over a range of N intakes have shown little difference between plant species, fed as fresh feeds, at the same N intake (fig. 5, Ulyatt and Egan 1979). However, the N content of white

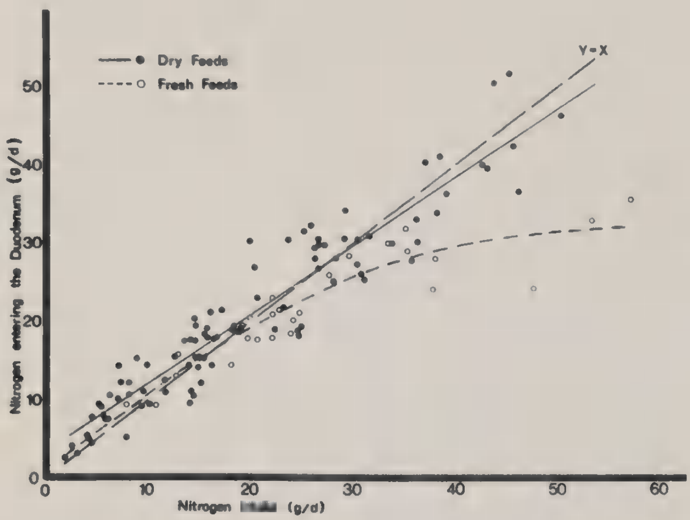

Figure 5--The relationship between nitrogen entering the duodenum (g/d) and the nitrogen intake (g/d) of sheep fed fresh and dry feeds.

clover is 14% higher on average than that of perennial ryegrass. Therefore, at the same OM intake, sheep consuming white clover would have a higher N flow at the duodenum as demonstrated in table 2 (M.J. Ulyatt, D.E. Beever, and D.J. Thomson, unpublished data). At the same OM intake, calves fed immature white clover (Period 5) had a 16% higher flow of N into the duodenum than those fed perennial ryegrass (Period 1). Rattray and Joyce (1969) also found increased N retention per unit of DOM intake in white clover (4.1% N) compared with perennial ryegrass (3.3% N). There may be circumstances under which the protein absorbed from white clover is utilized more efficiently at the tissue level than that from perennial ryegrass, but the predominant influence in determining performance per unit of intake in fresh diets appears to be the N content of the diet.

When the higher intake of white clover is also taken into account, differences in N flow at the duodenum are marked. In the experiments described by MacRae and Ulyatt (1974), sheep grazing ad lib. on white clover had a 51% higher flow of N into the duodenum

Table 2 - Nitrogen (N) digestion by calves fed perennial ryegrass and white clover at different stages of maturity in both indoor and outdoor experiments (M.J. Ulyatt, D.E. Beever, and D.J. Thomson, unpublished data). All intake data and non-ammonia nitrogen (NAN) duodenal flow data are adjusted to 200 kg liveweight

	Perennial ryegrass			White clover	
	Primary	Trimmed	Regrowth	Mature	Regrowth
Period	1	2	3	4	5
Indoor experiment					
OM intake (g/d)	4,400	4,400	4,400	4,400	4,400
N in diet (% DM)	3.4	2.4	2.2	3.8	4.3
N intake (g/d)	165	116	106	181	209
NAN entering duodenum (g/d)	133	114	113	134	155
Outdoor experiment					
Voluntary OM intake (g/d)	6,160	4,920	5,030	5,430	6,370
N in diet (% DM)	3.7	3.1	2.0	3.5	3.9
N intake (g/d)	251	167	110	204	276
NAN entering duodenum (g/d)	148	127	126	157	191

than those fed perennial ryegrass. Similarly (table 2), calves fed *ad lib.* received about one-third more duodenal N on white clover. Such differences must be the main cause of differences in feeding value between white clover and perennial ryegrass.

Management Techniques to Exploit Legumes

White Clover

Farming patterns and management techniques in New Zealand have developed in such a way that feed quality is sufficient to maintain livestock during winter. However, in both dairy and sheep farming, pastures of higher feeding value would significantly increase production in spring and summer. The likely additive benefits of increased legume in the diet mean that the low legume content of N.Z. pastures is a cause for concern.

Herbicides give the most dramatic increase in legume content. Paraquat spraying to induce white clover dominance in summer was assessed in the 1960's (Taylor and Arnst 1968). It is a reliable method, but problems of cost, weed infestation, and loss of total DM production have meant that the technique is not widely adopted by farmers. The technique was mainly aimed at increasing prime lamb production. Present low net returns for prime lamb mean that few farmers are willing to use this high-cost option for increasing legume content in their pastures.

In dairying, the sowing of larger leaved white clovers such as 'Grasslands Pitau', preferably after a crop, offers the best means for increasing white clover content.

In hill country sheep and beef farming, white clover levels can be increased by oversowing with 'Grasslands Tahora' white clover together with applications of phosphorus and lime. Where this can only be done on a paddock-by-paddock basis, it is important that these paddocks be intensively defoliated in spring and used for prime lamb production in summer and autumn. Cattle grazing and treading can increase white clover content (Clark et al. 1982a). This is a 'low cost' technique which has become increasingly feasible with intensive subdivision by electric fencing.

The possibility of using goats to prepare white clover-dominant pastures as well as to control weeds has been suggested by Lambert et al. (1981) and used by some farmers (Woodward 1981). The changes in clover content are larger than from cattle grazing, but the small number of goats farmed at present means that the technique does not provide a short-term answer to increasing clover contribution.

Other Legumes

The nutritional and hence economic advantages of lucerne, red clover, and lotus have been widely recognised by farmers in areas of New Zealand where white clover is unsuited. Efficient grazing control has minimised any short-term deleterious effects on stock health. The principle of using these species as a production rather than a maintenance ration is widely acknowledged. Utilisation problems are overcome by either 'leader-follower' grazing systems, with lower quality residues grazed only by stock requiring maintenance feeding, or by conservation as hay or silage. Reduced establishment costs, more persistent cultivars, and acknowledgment and understanding from research of their contribution to 'whole farm' enterprises would lead to more widespread acceptance.

Future Research

Voluntary feed intake from grass-legume pastures needs to be increased. Research should be directed at two areas: plant breeding and pasture management.

The quantity and quality of plant protein should be increased. Quantity might be improved by breeding for higher N content. Attempts to improve quality should concentrate on reducing the loss of soluble N across the rumen, perhaps by the incorporation of tannins.

The nutritional effects of grazing different combinations of legumes and grasses in mixed swards require examination. Present herbicide treatments need to be re-evaluated and new ones devised, for increasing legume content, and likely options integrated into farm management systems.

Alternative animal species (e.g., goats) should be studied further to increase the understanding of competitive interactions between legumes and associated grasses.

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Discussion

Sheath: Would you agree that one of the biggest factors in quality and intake is the ratio of dead and green matter? How might we change this, particularly where mechanical harvest and conservation are not possible?

Clark: Dead material has a much lower digestibility, and it is shown in the paper that sheep actively reject it. They maintain diet quality by selection, but this reduces their intake. A higher legume composition in the sward helps, but management must aim for better utilization. However, this is often achieved at the expense of animal performance. High-intensity farmers desperately need a higher quality feed.

Brougham: The authors left the impression that in all systems of N.Z. farming, N-intake is limiting animal production.

Ulyatt: This impression was not intended. The liveweight gain superiority of white clover over perennial ryegrass is associated primarily with the amount of protein available to the animal for absorption from the small intestine. As intake of fresh forages increases, the proportion of dietary N that enters the duodenum declines with sheep; there can be as much as 35% of dietary N lost this way at a N intake of 50 g/day. The loss results from

deamination in the rumen. Protein supplementation studies have shown that there are circumstances where ruminants respond in production. The full significance of this result has not been assessed. However, we are convinced that if the protein solubility of fresh forages could be reduced, there would be significant gains in animal production.

Minson: I don't necessarily agree with Marc. Ulyatt. The real question is--is there a protein shortage? Evidence of restricted diets on sheep show that protein supplements do show responses. At Massey, with cows, the answer is sometimes "yes" and at other times "no." Whichever way you look at the question, the legume has more protein, more energy, and is thus more needed in the animal diet.

Barry: When feeding fresh forage in high-intensity systems, there is a response to protein supplement. A factor is the length of trial. In short trials, the animal can mobilize nitrogen from body tissues.

Jorgensen: Do we know whether the requirement is for protein as such, or whether it is being converted to an energy source?

Ulyatt: We have evidence that it is a true protein response, probably meeting a methionine shortage.

Barry: In two trials at Ruakura, there was response to protein supplement but not to glucose. The deficiency, it would seem, is specifically part of the protein complementan amino acid possibly.

Lancashire: The paper has highlighted the importance of legumes in hill country pastures. Most of the hill country properties have considerable areas of land that can be cultivated, and hence should consideration be given to establishing special high-legume pastures?

Clark: Yes. However, these techniques must be looked at in terms of whole farm management. Early work with paraquat should be reevaluated under this approach, and new herbicides evaluated.

Nutritional Value of the Legume in Temperate Pastures of the United States

Gordon C. Marten[1]

Abstract

The high forage quality of legumes in temperate pastures of the United States is illustrated by the fact that ruminants have invariably performed better when grazing legume-grass rather than all-grass pastures. Generally, temperate legume species share excellent nutrient composition and digestibility at immature stages, and all usually contain 16% or more crude protein in the dry matter up to first flower stage. These species are generally rich in mineral elements needed for diets of high-producing ruminants, except deficiencies of P, Na, Cu, and Zn are likely to occur, and excessive Ca/P ratios usually exist. Whereas high animal intake potential (associated with low concentrations of cell walls) exists generally for the temperate pasture legumes, at least eight species are known to be relatively unpalatable to grazing animals when a choice is available. However, several experiments revealed superior performance by ruminants that grazed birdsfoot trefoil (Lotus corniculatus L.) without choice compared to alfalfa (Medicago sativa L.), even though birdsfoot trefoil is less palatable. On the other hand, two experiments revealed relatively inferior performance by cattle that grazed unpalatable cicer milkvetch (Astragalus cicer L.) compared to several more palatable legume species. Grain supplementation of high-quality pure legume pasture has usually resulted in increased daily gains by ruminants. The possibility exists that pure legume pasture forage has an excess of protein in relation to available energy and/or excessive soluble protein, which results in deamination in the rumen. At least eight major research thrusts are suggested to allow more complete exploitation of the great potential that temperate legumes have to supply the nutrient needs of high-producing ruminants.

Introduction

After review of 34 experiments in the United States, Canada, and Ireland, Reed (1981) concluded that temperate legume-grass pastures invariably provide better beef animal performance per head than do grass pastures fertilized with nitrogen (N). In his paper concerning productivity and economics of legume-based vs. fertilizer N-grass-based forage systems at this workshop, Burns presented evidence of the usually superior feeding quality of temperate legumes compared to grasses as pastures for beef and dairy cattle.

Reed (1972) also reviewed sheep-grazing experiments which revealed that animal daily gains on legume-grass pastures were usually greater than those on grass pastures.

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Also, Van Keuren and Hoveland (1984) reported that lambs grazing legumes alone or legume-grass mixtures generally gain better than do lambs grazing grasses alone. Minnesota experiments (Marten and Jordan 1979; Jordan and Marten 1983; G.C. Marten and R.M. Jordan, unpublished data) revealed that lambs gained better when they grazed pure perennial or annual legumes compared to legume-grass mixtures, pure grasses, or nonleguminous forbs.

Among the factors responsible for the improved performance of ruminants that graze temperate legumes compared to grasses are greater intake, a more rapid rate of digestion, superior efficiency of nutrient utilization, and greater concentration of specific minerals in legumes (Templeton 1976).

Minson (1981) listed three desirable and four undesirable feeding value factors that should be considered in quest of a "nutritionally ideal grazing plant." The desirable factors are: (1) mineral composition, to meet the varying requirements of ruminants; (2) protein, not lower than 7% and up to 16% or more of the dry weight for high-producing ruminants; and (3) energy digestibility, about 80% (including high cell contents and high digestibility of cell walls). The undesirable factors are: (1) poor spatial distribution so as to be inaccessible to the grazing animal (so that bite size is inadequate); (2) low intake due to excessive indigestible or slowly digestible fiber (including steminess); (3) presence of characters that reduce the preference of livestock for the forage when a choice is offered (lack of palatability); and (4) toxic and estrogenic compounds. I will consider the presence of the desirable factors, and the palatability and intake components of the undesirable factors, listed by Minson (1981) as I review the nutritional value of some of the temperate legumes that are grazed in the United States.

Pasture Quality of Legume Species

Organic Nutrient Composition and Digestibility

Alfalfa (Medicago sativa L.), red clover (Trifolium pratense L.), birdsfoot trefoil (Lotus corniculatus L.), and ladino (white) clover (Trifolium repens L.) are the dominant forage legumes used in pastures and for conserved forage in the temperate regions of the United States. A series of Wisconsin reports (Van Riper and Smith 1959, Baumgardt and Smith 1962, Smith 1964) compared the chemical composition and nutritive value of these legume species as they advanced in maturity from vegetative (as little as 10 cm growth) to seed stages of both spring and summer growth. If one considers their first three of four growth stages (until early flowering) as representative of pasture conditions, then the following conclusions apply regarding nutrient composition:

1. Crude protein concentration never fell below 18% dry wt, and it peaked at about 30% or higher.

2. Ladino clover often contained more crude protein and less crude fiber than the other three species without as much change due to maturation (recently confirmed by Buxton et al., 1983, who reported that

white clover had the smallest digestibility and protein declines of the four species as plants matured).

3. Red clover and birdsfoot trefoil often contained less crude fiber than did alfalfa.

4. Red clover, ladino clover, and birdsfoot trefoil contained more estimated total digestible nutrients (TDN) or estimated digestible dry matter than did alfalfa, but all four species reached 80% or more estimated TDN at prebud or earlier stages of maturation.

We have monitored the relative nutritive value of several legumes grazed by ruminants in pure stands over complete seasons in Minnesota. Because we use controlled grazing pressures, our procedure of sampling fresh forage for laboratory analysis from each pasture just prior to animal entry in a rotational grazing scheme should give a meaningful assessment of the relative quality of various legume species available to and consumed by the animals. In a lamb grazing experiment (Marten and Jordan 1979), we found that as the legume composition of an alfalfa-perennial grass system was increased from a mean of about 60% legume (by substituting pure birdsfoot trefoil instead of alfalfa-grass as one-third of the total system), we increased available in vitro digestible dry matter from 71% to 73% dry wt; cell contents from 52% to 54%, and crude protein from 18% to 19% during a 3-yr period. These changes (either of themselves or in association with the fact that birdsfoot trefoil rather than alfalfa comprised up to about one-third of the total legume consumed during a season) caused from 22% to 24% increases in lamb average daily gains.

In other ongoing and unpublished grazing studies, we have found nutritive value differences among pure legumes grazed by either sheep or dairy heifers (table 1). We found that whereas birdsfoot trefoil may contain slightly more in vitro digestible dry matter (IVDDM) than alfalfa at times, this was not a consistent or statistically significant difference. Also, crude protein concentration of the two species was similar, but neutral detergent fiber was somewhat lower in birdsfoot trefoil. Kura clover (Trifolium ambiguum Bieb.) had similar or somewhat less crude protein concentration than alfalfa and birdsfoot trefoil, but the clover had decidedly superior digestibility. Cicer milkvetch (Astragalus cicer L.) had similar crude protein concentration as alfalfa and birdsfoot trefoil, similar (although variable) digestibility, but lower neutral detergent fiber. The latter characteristic is probably partly explained by the greater leaf-to-stem ratio of cicer milkvetch. Crownvetch (Coronilla varia L.) had digestibility much like alfalfa and birdsfoot trefoil, but it had more crude protein than either. Sainfoin (Onobrychis viciifolia Scop.) had lowest crude protein and lowest IVDDM, even though it had the highest leaf-to-stem ratio and neutral detergent fiber concentration similar to that of alfalfa.

All the legumes, including sainfoin, contained at least the 16% crude protein that Minson (1981) listed as part of his definition of the nutritionally ideal grazing plant. Only kura clover consistently met his standard of 80% energy digestibility, but the grazing animals were not forced to consume all the available forage, so they undoubtedly selected higher quality material than that which we assayed.

Two recent experiments illustrated the considerable variation in quality of specific legume plant parts that may be selectively grazed by sheep and cattle (McGraw and Marten, unpublished data; Buxton et al. 1983). For example, leaves of alfalfa and birdsfoot trefoil in Minnesota maintained IVDDM concentrations greater than 80% during maturation from vegetative to full flower stages (May 3 to June 28), whereas IVDDM of their stems ranged from about 80% in early May to about 55% in late June. On the other hand, IVDDM of sainfoin leaves ranged from 76% to 68%, and that of sainfoin stems ranged from 85% to 52%, during the same period. Also, sainfoin forage had a considerably higher leaf/stem ratio throughout the season, but especially early in the season and during regrowth, compared with alfalfa or birdsfoot trefoil.

We also examined forage quality in stratified canopies of alfalfa, birdsfoot trefoil, and red clover grown in Iowa (Buxton et al. 1983). The IVDDM of alfalfa and birdsfoot trefoil stems decreased with maturation about twice as fast as that of the total herbage; stem bases had less IVDDM than did stem tops (the rate of change within stem segments from top to bottom was about 2% IVDDM per node). In contrast to alfalfa and birdsfoot trefoil, red clover had very digestible stems. In fact, red clover stems had greater concentrations of IVDDM than did leaves until flowering occurred; the rate of change within red clover stem segments from top to bottom was less than 0.8% IVDDM per node. Therefore, simply measuring leaf/stem ratios of pasture legumes and genetic selection for leafiness may be of value within species, but it may also give misleading forage quality assessments among species. Kühbauch (1981) suggested that it was possible to estimate the forage quality of alfalfa and red clover (but not white clover) by simply measuring stand height, stem length, and leaf/stem ratio.

Mineral Composition

According to Butler and Jones (1973), elements essential to animals differ from those essential to plants in that animals have substantial requirements for iodine (I), cobalt (Co), selenium (Se), and sodium (Na). Many deficiencies in grazing animals are, therefore, associated with these elements, because normal pasture growth can occur on soils deficient in them. Fleming (1973) stated that the "generally accepted view" is that both temperate and tropical legumes are richer in mineral elements than are grasses. However, Dennis J. Minson emphasizes in "Nutritional Value of Tropical Legumes in Grazing and Feeding Systems," earlier in these proceedings, that the Na content of most tropical legumes is low to very low compared to that in temperate legumes and grasses. Fleming cited research showing that the Na content of white clover was higher than that of alfalfa which in turn was higher than that of red clover. Smith (1964) reported that the only striking mineral composition difference between alfalfa and birdsfoot trefoil in Wisconsin was that

Table 1 - Nutritive value (% dry wt) of pure stands of legumes grazed by ruminants during two studies involving complete pasture seasons in Minnesota (G.C. Marten et al., unpublished data)[1]

Study A

Species	Crude protein			In vitro digestible DM		
	1981[2]	1982[3]	1983[4]	1981[2]	1982[3]	1983[4]
Alfalfa	19.9bc	23.0b	24.4c	71.0b	76.3b	75.8b
Birdsfoot trefoil	21.2ab	23.0b	26.6b	73.1b	76.4b	78.9ab
Sainfoin	16.0d	17.5c	15.7e	65.2c	66.4d	71.4c
Cicer milkvetch	20.9bc	23.8b	23.4cd	72.2b	72.0c	80.9a
Crownvetch	23.2a	26.4a	28.9a	72.6b	75.4bc	78.9ab
Kura clover	18.7cd	21.6b	22.0d	81.4a	82.2a	82.3a

Study B

Species	Crude protein[5]	Neutral detergent fiber[5]	In vitro digestible DM[5]	Leaf/stem[5]
Alfalfa	23.1a	36.8a	72.5a	0.8
Birdsfoot trefoil	21.4b	33.8b	73.2a	1.2
Sainfoin	18.7c	35.7a	68.1b	2.7
Cicer milkvetch	21.1b	30.1c	69.4b	1.5

[1]Means within assays within years followed by different letters are different ($P \leq 0.05$; LSD).

[2]Means of three replicates and four harvests.

[3]Means of three replicates and three harvests.

[4]Means of three replicates of June 1 harvests.

[5]Means of three replicates and seven intermittent samplings during a 99-day grazing experiment in 1983.

birdsfoot trefoil contained less than half as much Na as did alfalfa.

Ehlig et al. (1968) compared Se uptake by numerous forage species to that by alfalfa in both field and glasshouse studies. Accumulation of Se did not vary greatly among species in soils having low amounts of Se. However, field samples of red clover contained half the Se of alfalfa, and Astragalus bisulcatus (Hook) Gray (a noted Se accumulator) had about five times as much Se as alfalfa grown in a neutral silt loam to which labeled Se was added. Fleming (1973) also emphasized that the relative mineral uptakes by different species may vary depending upon the soil. Generally, the effects of fertilization with elements other than N are directly expressed on the inorganic composition of forage plants (Reid and Jung 1974).

Although marked differences of opinion exist in the literature concerning the mineral requirements of various categories of animals, Reid and Jung (1974) reached three major conclusions: (1) the potassium (K) requirements of forage plants for normal growth are so high relative to animal needs that K deficiency of grazing animals should not occur; (2) the requirements of animals for magnesium (Mg), especially of milking animals early in the grazing season [as well as for Na, chlorine (Cl), I, Co, and Se] exceed requirements for normal plant growth, so these elements may need to be supplied in feed supplements or in fertilizer; (3) the requirements of the animal and the plant for a given mineral [such as phosphorus (P)] may be equivalent, so a deficiency will depress the productivity of both. Also, Hill and Guss (1976) claimed that the most critical departure of legume forage mineral supply from animal requirements was the excess calcium (Ca) in legumes. Excess Ca interferes with utilization of some trace elements, and high Ca/P ratios in the diets of nonlactating dairy cows may predispose them to later milk fever. They reviewed literature which revealed that alfalfa, white clover, and red clover provided most of 10 mineral elements required by dairy cattle, although deficiencies occurred for P, Na, copper (Cu), and especially zinc (Zn).

Hill and Jung (1975) estimated the potential ranges of mineral concentration in alfalfa that could be achieved through plant breeding (based on a quantitative genetic analysis). They concluded that: (1) P-deficiency could be corrected (relative to needs of a moderately producing dairy cow); (2) correction for Zn-deficiency and for the excessive Ca/P ratio would be possible, but difficult; and (3) deviations from dairy cow requirements for Cu (deficiency), Na (deficiency), K (excess), and Ca (excess) could not be corrected through plant breeding without alteration of soil fertility.

In practice, the majority of livestock producers who utilize temperate legumes for ruminant grazing in the United States allow free access by the animals to salt blocks or other additives that contain NaCl fortified with other minor elements known to be deficient. Therefore, the topic of mineral concentration of grazed legumes has not received greater attention. However, we recognize that supplementation of pasture forage with minerals is not as easily accomplished as is mineral supplementation of conserved feeds.

Palatability and Intake

Marten (1981) reviewed research concerning palatability problems (rejection when a choice is offered in the presence of palatable plants) associated with the occurrence of deleterious compounds in forages, including pasture legumes. Among the species reported to have palatability problems and the suspected causal agents are: sericea lespedeza (Lespedeza cuneata L.)--tannin in leaves as well as stiff, coarse stems; Lupinus and Crotalaria spp.--alkaloids; and sweetclover (Melilotus alba Desr.)--coumarin. Plant breeders have developed more palatable cultivars of these species by reducing concentrations of causal agents.

Among the legume species reported to be unpalatable for which no specific causal agent has been identified are crownvetch, cicer milkvetch, Astragalus adsurgens Pall. (Wenhui 1981), and birdsfoot trefoil. Whereas the latter species is a leading pasture legume in the United States, we have observed that it is less palatable to sheep and cattle than is alfalfa upon first exposure in spring grazing. Also, Rabas (1983) stated that northern Minnesota farmers have claimed that livestock found birdsfoot trefoil lower in palatability than many other legume and grass species to the point that they were concerned about animal performance on birdsfoot trefoil pastures.

The intake potential of temperate pasture legumes in general is greater than that of perennial temperate grasses because of the lower cell wall concentrations of the legumes. This is true even though immature temperate legumes and grasses often have similar concentrations of digestible energy (Donker et al. 1976). Thornton and Minson (1973) considered that the generalized nutritive advantages for legumes compared to grasses included more rapid digestion of dry matter, greater density of the rumen liquor, lesser cell wall concentration, lesser animal retention time, and resultant greater intake.

Grazing Animal Performance

Few grazing experiments have been conducted in the United States in which pure stands of legume species have been assessed for their comparative animal performance potential. Gray (1981), in Nebraska, reported that yearling steers gained 0.87 kg/day on irrigated alfalfa pasture compared to 0.73 kg/day on cicer milkvetch, even though the two species contained nearly identical concentrations of crude protein (22%) and IVDDM (69%), and the animals also received 0.45 kg of corn grain/head/day (which negated comparison of feeding value per se of the legumes.

We are in the second full year of a Minnesota grazing study with dairy heifers that receive either alfalfa, sainfoin, birdsfoot trefoil, or cicer milkvetch as their sole sources of feed energy and protein for complete growth periods (G.C. Marten and F.R. Ehle, unpublished data). We are testing a first hypothesis that the presence of tannin in birdsfoot trefoil and sainfoin and the absence of

tannin in alfalfa and cicer milkvetch could differentially influence rumen bypass (escape) protein and, hence, the efficiency or extent of weight gain in cattle. We are also testing a second hypothesis that palatability variation in these legumes could affect the gain of cattle that are obligated to eat either palatable or unpalatable species for complete grazing seasons.

Table 2 presents the average daily gains by the heifers that grazed these species during a 99-day grazing season that had good moisture distribution in 1983. The two tannin-containing legumes (birdsfoot trefoil and sainfoin) provided the highest animal performance. The least palatable species (cicer milkvetch) provided much lower gains that did the other species, all of which were much preferred when a choice was offered. The usual quality measurements (crude protein, neutral detergent fiber, or IVDDM), as shown in table 1 (Study B) could not explain the relative animal gain, even though we controlled grazing pressures. Neither could differences in morphological traits such as leaf/stem ratio, except that alfalfa (low gain) was less leafy than was birdsfoot trefoil or sainfoin (high gain).

We are currently seeking the reason for the very poor palatability of cicer milkvetch and for an unexpected severe outbreak of photosensitization only among heifers that grazed cicer milkvetch in 1983. Low intake was an obvious problem in cicer milkvetch pastures, because the available forage was never consumed to the degree of the other pastures, even though initial animal numbers during each 14-day grazing period were decided based on yield of forage dry matter per unit area ("put-and-take" system).

The superior performance of heifers grazing birdsfoot trefoil in the above experiment confirms our earlier results (Marten and Jordan 1979). In the latter study, substitution of pure birdsfoot trefoil for alfalfa-grass as one-third of the total seasonal pasture resulted in 22% to 24% increases in lamb average daily gains over a 3-year period.

Grain Supplementation of Legume Pastures

Although pasture legumes have frequently stimulated superior animal performance above that acquired from grasses, and digestible energy intake by ruminants from legumes can be greater than that from grasses, some evidence indicates that intake of digestible energy and/or effective utilization of digestible energy from high-quality legume pasture are not sufficient to meet the needs of high-producing animals. Therefore, supplementation of even the best quality pasture with concentrates often leads to improved animal performance.

Mott et al. (1968) found that feeding cattle grain when they grazed a mixture of birdsfoot trefoil, white clover, and perennial grasses in Indiana resulted in about 0.1 kg/day gain improvement per animal for each 1 kg/day of grain fed per animal. However, as the level of grain increased, its apparent feed efficiency decreased. Lake et al. (1974) reported similar results with steers that grazed an irrigated mixture of alfalfa and perennial grasses. Stricker et al. (1979) also reported that nursing calves receiving a grain creep feed weighed 32 kg more at weaning than those not receiving creep feed on ladino clover-grass pastures in Missouri.

Lowery et al. (1976a and 1976b) found very poor conversion of concentrate to animal gain when steers grazed a clover-grass mixture, apparently because concentrate simply substituted for the high-quality pasture forage (rather than being additive). In a lamb grazing study in Minnesota (Jordan and Marten 1983), we found that the economic and biological

Table 2 - Relative palatability of four legume species when a choice was offered to heifers in a 2-year cafeteria trial compared with average daily gains by heifers that grazed without choice for 99 days at Rosemount, Minnesota, in the second year

Species	Relative palatability score (10 = rejection) 1982	1983	Heifer daily gain (kg), 1983
Alfalfa	3.0	3.9	0.63b (100%)
Sainfoin[1]	3.6	4.4	.81a (129%)
Birdsfoot trefoil[2]	4.7	4.5	.86a (137%)
Cicer milkvetch[2]	10.0	9.7	.34c (54%)
			LSD 0.05 = 0.16 kg

[1]Because of delayed regrowth of this species, the heifers grazed on alfalfa reserve pastures from 7/22 to 8/1 (10 days) of the 99-day period.

[2]Because of delayed early growth of these species, the heifers grazed on alfalfa reserve pastures for the first 5 days of the 99-day period.

efficiency of feeding ad libitum grain supplement was least when the quality of the forage was greatest (when pure alfalfa constituted the pasture compared to alfalfa-grass). This agreed with the conclusion of Coleman (1977) that animals grazing good-quality pastures substitute more concentrate for forage than do cattle grazing poor-quality pastures. It also supported Moore's (1978) contention that management decisions on the use of supplements should depend on knowledge of forage quality and the additive vs. substitutive effects of concentrate feeds.

However, substitution of energy from added concentrates for that from high-quality pasture forage is not consistent. For example, we obtained a 3-year mean increase of 57% in average daily gains of grazing lambs by ad libitum feeding of grain on high-quality pure alfalfa pasture (Jordan and Marten 1983). Lambs receiving ample amounts of only alfalfa pasture gained a mere 0.14 kg/day, whereas those receiving grain on the same high-quality pasture gained 0.22 kg/day. Because we wanted controlled (light) grazing pressure, we forced equivalent utilization of the alfalfa on grain and nongrain treatments by use of additional "grazers" on the grain treatment. We concluded the possibility existed that the high degree of solubility of the protein in the alfalfa (total available pasture had digestible dry matter >70% and crude protein >20% dry wt) did not allow the protein to be efficiently utilized unless it was fed in conjunction with a more concentrated form of energy (the grain). The research of Hemsley et al. (1970), which showed that treatment of clover-dominant forage (25% crude protein) with formaldehyde reduced deamination in the rumen of sheep and increased wool production, supported this possibility. Also, Lake et al. (1974) found that increasing energy supplementation of alfalfa-grass pasture in Nebraska caused decreases in blood urea nitrogen and increases in urinary creatinine-nitrogen ratios in yearling steers; this suggested that the pasture forage contained an excess of protein or N in relation to its available energy.

Temperate Pasture Research Needs

Several major research thrusts are needed to exploit further the already great potential of forage legumes to supply high-quality pasturage to meet the nutrient needs of high-producing ruminants:

1. We should seek methods of retaining in the mature legume plant the high nutritive value and intake potential of the immature plant (for example, reduction of leaf loss and stem lignification via inexpensive chemical treatment in situ or breeding for greater leaf percentage and higher quality stems within species).

2. We need to more thoroughly determine the influence of anatomical and morphological variables and spatial orientation within and among legume populations on nutritive value and animal response.

3. We must assess the biological and agricultural significance of palatability variation among and within legume species, especially within those species already known to have relatively poor palatability (for example, cicer milkvetch, crownvetch, and birdsfoot trefoil). If the palatability problem proves to be detrimental to animal performance when no alternative choice of forage is provided, there may be merit in attempting to find the causal agent so that plant breeders can select palatable genotypes and breed palatable cultivars. If the palatability problem is not detrimental to animal productivity per se, investigation of the problem may still have merit in that superior "matches" of legumes and grasses of similar palatability can be achieved to provide more easily managed pasture mixtures.

4. Continued search for antiquality constituents in problem pasture legume species (for example, cicer milkvetch) that have considerable agronomic potential is definitely merited. If the causal or preventive agents of maladies such as bloat and photosensitization can be identified, we can breed cultivars or manage pastures to minimize or eliminate their influence.

5. Selection of legume species or breeding of cultivars within species for accumulation of minerals now known to be deficient in grazing animal diets (such as P) would be beneficial.

6. We should determine if there definitely is a crude protein/energy imbalance in high quality legume pasturage and, if so, how to overcome it. We must use pure stands of grazed legumes initially in order to clearly define nutritional status of consumed forage. Then mixtures should be introduced to determine effects of species combinations.

7. We need to assess whether "rumen bypass protein" or related phenomena are involved in the superior animal gain responses recently achieved by grazing ruminants on tannin-containing compared with tannin-free legumes and/or whether tannin per se is even responsible for the gain differences. If tannin or some other chemical factor is involved, we must determine how best to utilize the information to enhance animal performance.

8. We must devise complete legume-based grazing systems to exploit the strengths and avoid the weaknesses of various species alternatives. Several species utilized in pasture sequences may provide superior grazing systems compared with those being used today.

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Discussion

Easton: Is the problem of P shortage in the diet of sufficient importance to justify a breeding program?

Marten: In high-producing dairy cows, the low intake of P in the forage combined with low availability can limit production. As P content is a heritable factor, it can be manipulated by breeding.

Lancashire: The first table showed the feed quality analysis of sainfoin to be poor, and yet live-weight gains were good?

Marten: Palatability is ranked somewhat lower than that of alfalfa when grazing animals have a choice. However, without choice, intake is good. We do not know why. Regrowth is slow and leafy.

Lancashire: N.Z. experience is that feeding value of sainfoin is high.

Barnes: Work at Grass Research Institute in U.K. showed very high intake values.

Marten: But pasture palatability as such is not high. There is something else.

Barry: Tannins in a plant have contrasting effects. They protect protein in the rumen but may depress intake. The molecular weight of the tannins in sainfoin is very favourable in this respect.

Easton: Limited N.Z. farmer experience indicated that stock acceptability of sainfoin is very high.

Ulyatt: There appears to be something enabling quick breakdown and rapid passage through the rumen.

Marten: Initial stem development is slow with sainfoin, and with the same harvest schedule it may be leafier than other legumes. However, stems develop rapidly as maturity approaches and their quality is low.

Ulyatt: Nonbloating is another factor.

Marten: We treated to eliminate bloat as a factor in the trials when it developed from alfalfa.

Barry: Are there data on voluntary intake of sainfoin? This is the missing element in N.Z. data.

Marten: There are no detailed voluntary intake data that I know of in the United States. Research on sainfoin is meager. Limited studies indicate equivalent intake of sainfoin and alfalfa hay by sheep and cattle.

Barnes: Do we know anything of the type of structural components--the nature of the lignins for example?

Marten: No.

Barry: The two species with tannins researched in New Zealand are also high in lignins. Experimentally it is difficult to dissociate the two effects.

Minson: Will animals eat the thick stems of sainfoin?

Marten: No, not on pasture.

Minson: Do you consider that yields of legumes with high stem contents should be expressed on the basis of edible material?

Marten: Yes.

Rumbaugh: Part of the problem of the photosensitizing effect on animals that grazed cicer milkvetch could be that it was in a pure sward. Considerably less will be consumed and a better nutritional balance may be obtained in a mixed sward.

Jorgensen: We have a photosensitization of rats fed alfalfa concentrate.

Marten: I have heard that a similar thing was observed in pigs in New Zealand.

Ulyatt: That was at Palmerston North. The work has been published, but I do not recall what the factor was.

Keeney: Has anything been done on trace elements--in particular selenium (Se)?

Marten: There is no proven Se deficiency in Minnesota, although it may occur in other States including parts of Wisconsin and Eastern States. Some of our Western States have Se toxicity.

Nutritional Value of Legumes Preserved as Hay

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Abstract

Forage quality is the first limiting factor in ruminant production in many areas of the United States. Livestock producers will invest in higher quality forages if: (1) forages represent a large portion of the diet, (2) animal performance is increased by improving forage quality, and (3) increased animal performance leads to higher profits. Dairying represents a major target for forage quality grading systems. This is due to the great limitations that fiber components of the ration impose upon intake, digestibility, and efficiency of nutrient utilization. The relative feed value of alfalfa, as predicted by the hay grading system proposed by the Hay Marketing Task Force of the American Forage and Grassland Council, was evaluated with high-producing dairy cows. The results reveal that the measured and predicted relative feed values were similar. Early cut alfalfa was worth more than 130% that of mature alfalfa. The quality of hay legumes is affected by species, maturity, and harvesting and storage conditions.

Introduction

Hay is one of the major crops grown in the United States. Over 100 million ha of hay were harvested in 1982. While most of the hay is utilized on the producing unit, an increasing amount is being marketed as a cash crop. There are extreme variations in quality. Although marketing on the basis of quality tests is increasing, most hay is purchased on trust between buyer and seller. The best measure of forage quality is animal productivity. Productivity is the result of intake, digestibility, and efficiency of utilization of absorbed nutrients (Waldo and Jorgensen 1981). Therefore, an important consideration in forage evaluation is the use of the analytical measurements which can be used to estimate intake, digestibility, and animal performance.

Harvesting a high-quality legume crop is largely dependent upon weather conditions. Losses during hay curing result from respiration, leaf loss, and leaching (Murdock 1964). Losses due to rainfall during field drying are related to mechanical treatments, amount of rainfall, number of showers, and dry matter percentage of the forage at time of wetting (Collins 1982). High-quality hay can be obtained if consideration is given to plant maturity at harvest, reduction of weather exposure during drying, and prevention of leaf shatter.

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Harvesting

The Drying Process

The field-drying process depends not only on weather conditions, but on the drying behavior of the plant tissue. The latter is influenced by stage of maturity, leaf-to-stem ratio, structure of the swath, and conditioning efforts. Energy for dehydration is provided by the drying air (temperature and speed), self-heating from continued cellular respiration, and activity of micro-organisms (Klinner and Shepperson 1975). Solar radiation has a dominant effect on moisture loss. Under field conditions, a wind speed of about 2.2 m/sec appears most effective for moisture removal from plant tissue. However, soil moisture can influence drying rate. Cellular respiration continues until the tissue moisture is less than 40%.

The aim in haymaking is to have a rapid drying rate associated with minimum dry matter and nutrient loss.

Dry Matter and Nutrient Losses

Dry matter (DM) losses associated with field curing and harvesting range from 3.5% to over 40%. A larger proportion of leaves compared to stems is lost in the haying operation. Thus, the resulting hay may contain less protein, carotene, minerals, and energy, and more fiber than the standing crop (Jorgensen 1982, Ehle 1983). With good drying conditions, respiration losses range from 2% to 8% of crop DM; with poor conditions, up to 16% of the DM may be lost (Klinner and Shepperson 1975). Mechanically induced losses include those from cutting, 1% to 6%; conditioning, 1% to 5%; raking, 5% to 20%, and baling, 3% to 15% for small rectangular bales (18-25 kg). Dry matter losses may be greater than 40% of the potentially available DM in the standing crop (Klinner and Shepperson 1975, Kjelgaard et al. 1983). Dry matter and nutrient losses are greater when hay is packaged in large round bales (250 to 800 kg). While conditioning may increase DM loss due to leaf shatter, it decreases loss of total nonstructural carbohydrates during good drying conditions, but increases losses during rainy weather.

Wetting legumes during field drying results in increased percentage nitrogen and fiber, but a decrease in percentage leaf, total nonstructural carbohydrate, and digestibility (Collins 1982). Losses due to wetting vary with legume species and the timing and duration of wetting. Rain damage increases loss of both dry matter and quality.

Nutrient content of hay may also be affected by season, which relates to weather conditions. Collins (1983) demonstrated that potential exists for autumn utilization of legumes produced following late August harvest. Yield was influenced by species and year and declined after mid-October. However, quality was high unless leaching of nutrients occurred due to rainfall.

Consumption of potentially available DM in the standing crop by dairy cattle was estimated to range from 72% to 76% when alfalfa was field-cured, packaged as small rectangular bales, and stored indoors compared

with about 50% to 52% for large round bales stored outdoors (Jorgensen 1982, Kjelgaard et al. 1983).

Chemical Treatment

Chemical treatments have been directed at either increasing drying rate to reduce exposure time or at reducing field exposure by baling at higher than recommended moisture levels. Ehle (1983) reviewed the topic of chemical conditioning of forages to be processed as hay. Applying K_2CO_3 to the stems just ahead of cutting, followed by conditioning, reduced drying time to baling (Johnson et al. 1983). The same effects were observed from potassium or sodium carbonate. Treating alfalfa with 3% to 4% (wet forage weight) of a solution of 2.8% K_2CO_3, 5% methyl esters of long chain fatty acids, and an emulsifier reduced field losses and improved forage quality. The goal is to increase drying rate of the stems so that stems and leaves reach the desired baling moisture level at the same time. This reduces loss of DM due to leaf shatter during mechanical handling of the forage.

Baling at 25% moisture or more reduces field losses (Hundtoft 1966, Kjelgaard et al. 1983), but increases storage losses. Application of 1% propionic acid or 1% to 2% anhydrous ammonia to forage baled with up to 30% moisture reduces spoilage due to molds and heating (Knapp et al. 1974, Jorgensen et al. 1978). Several chemicals, including mixtures of propionic-acetic acid or propionic acid-formaldehyde, show promise, but none are routinely used. Application of 1% to 2% anhydrous ammonia (wet forage basis) to high moisture hay stored in covered stacks provides adequate preservation. However, preservation is not obtained in uncovered stacks. Use of anhydrous ammonia for preservation of wet hay is in a research phase; no general application is made at the farm level.

Chemical Composition of Legumes

Species

Smith (1964) documented many previous studies on changes in chemical composition of alfalfa, red clover, and birdsfoot trefoil with stage of growth in both spring (first growth) and summer (second growth) growths. Chemical composition at two of the six stages of growth is summarized in table 1. Although chemical composition varied with species, the greatest differences were due to stage of maturity. Change in neutral detergent fiber (NDF) concentration and in vitro dry matter disappearance (IVDMD) of three legumes harvested at four maturity stages is summarized in table 2 (Collins 1981). While differences in quality were not great, yields of red clover and birdsfoot trefoil were less than that of alfalfa. Obierike (1980) and Rohweder (1984) reported that improvement in quality can be obtained by selecting varieties that produce high yields of crude protein and digestible energy. Highest dry matter yielding varieties may not always be those that yield the highest quality feed. Increased yields may be due to fiber which decreases quality.

Hay Grades Based on Chemical Tests

Proposed hay grading standards, tables 3 and 4, are based on chemical components and organoleptic characteristics (Rohweder et al. 1978, Rohweder et

Table 1 - Chemical composition of four legumes at two stages of growth and from first and second growths during specific seasons

Stage of growth	Growth	%, Dry matter basis			
		Crude protein	Crude fiber	Ash	Nitrogen-free extract
	Alfalfa				
Early bud	First	22.2	22.8	9.5	42.7
	Second	23.1	23.4	9.3	42.6
Full bloom	First	15.5	32.2	8.6	42.4
	Second	19.3	29.7	7.2	42.0
	Medium red clover				
Early bud	First	23.0	17.0	10.5	46.6
	Second	23.7	14.8	10.0	48.9
Full bloom	First	13.9	27.4	7.8	49.0
	Second	17.2	26.5	8.0	45.6
	Birdsfoot trefoil				
Early bud	First	21.3	15.8	10.1	50.1
	Second	22.2	17.5	9.1	49.0
Full bloom	First	17.0	27.0	6.8	47.2
	Second	20.9	24.5	7.7	44.2

Source: Smith (1964).

al. 1983, Kawas et al. 1983). For a forage to be of high quality, it must be high in three factors: (1) intake, (2) digestibility, and (3) efficiency of utilization (Waldo and Jorgensen 1981). The factor of high intake must include the desirable subfactor of high substitution for concentrate. The factor of high digestibility divides into three subfactors: (1) the total cell wall fraction is split into potentially digestible cell walls and indigestible cell walls (the potentially digestible cell walls must be high), (2) the fractional rate of digestion of the potentially digestible cell walls must be rapid, and (3) the depression of digestibility at high intakes must be minimal. A decrease in cell walls (1) increases intake substitution value of forage for concentrate, (2) increases digestibility

Table 2 - Quality changes with maturity of alfalfa, red clover, and birdsfoot trefoil

Harvest date[1]	Alfalfa		Red clover		Birdsfoot trefoil	
	NDF[2]	IVDMD[3]	NDF	IVDMD	NDF	IVDMD
27 May	36.9	71.0	26.6	80.0	26.7	77.0
2 June	42.3	67.9	33.4	74.9	33.1	72.2
9 June	43.2	65.1	35.9	70.9	36.1	68.8
16 June	45.2	61.3	38.0	68.7	37.3	66.5

[1]Maturity stage on 27 May: alfalfa, early bud; red clover, vegetative; birdsfoot trefoil, vegetative.
[2]NDF (neutral detergent fiber) % DM basis.
[3]IVDMD (in vitro dry matter disappearance) %.

Source: Collins (1981).

Table 3 - Proposed market hay grades for legumes, grasses, and legume-grass mixtures

Grade[1]	Brief description	Crude protein	% (DM basis) Acid detergent fiber	Neutral detergent fiber
Prime	Legume, prebloom	>19	<30	<39
1	Legume, early bloom, 20% grass-veg.	17-19	31-35	40-46
2	Legume, mid bloom, 30% grass-E. Headed	14-16	36-40	47-53
3	Legume, full bloom, 40% grass-Headed	11-13	40-42	53-60
4	Legume, full bloom, 50% grass-Headed	8-10	43-45	61-65
5	Mostly grass-Headed	<8	>46	>65

[1]Grade 6 = sample grade.

Source: Kawas et al. (1983).

Table 4 - Estimated digestibility, intake, and relative feed values for the proposed market hay grades

Grade	DDM[1] (%)	DMI[2] Sheep	DMI[3] Cattle	DDMI[4] Maint.	DDMI[5] 3X Maint.	Relative[6] feed value (%)
		-----------------	-----------------	$g/KgW^{0.75}$	-----------------	
Prime	>65	>82	>143	>93	>89	>132
1	62-64	76-81	133-142	83-92	78-88	118-132
2	58-61	72-75	122-132	71-82	67-77	101-117
3	56-57	63-71	110-122	62-70	59-66	88-100
4	54-55	56-62	98-109	53-61	50-58	75-87
5	<53	<56	<98	<52	<49	<75

[1]DDM = digestible dry matter, in vivo, = 102 + 0.008 CP% - 0.382 ADF% - 4.63 $\sqrt{\text{ADF\%}}$.
[2]DMI = dry matter intake sheep = 96.4 - 0.0003 CP% - 0.0482 NDF% - 0.0085 $\text{NDF\%}^2$.
[3]DMI = dry matter intake cattle = (DMI sheep x 1.75).
[4]DDMI = digestible dry matter intake cattle at maintenance level of intake = (DDM x DMI cattle) ÷ 100.
[5]DDMI for dairy cattle based on intake 3X maintenance = (DDM x 0.95) (DMI cattle) ÷ 100.
[6]Relative feed value = DDMI Maint. x 1.435.

Source: Kawas et al. (1983).

by increasing the fractional rate of digestion of the potentially digestible cell walls, and (3) decreases the depression of digestibility at high intakes.

Neutral detergent fiber (NDF), assay to measure cell walls (comprised of hemicellulose, cellulose, lignin, lignified N, and insoluble ash), is inversely correlated with intake and digestibility of forages (Mertens 1973, Osbourn et al. 1974, Rohweder et al. 1978). However, acid detergent fiber (ADF), which is composed of a large proportion of indigestible fibrous constituents (cellulose, lignin, and insoluble ash), is more highly correlated with digestibility than is NDF. NDF has the greatest correlation with voluntary intake. This may be due to the relationship between NDF and bulk density of feedstuffs (Mertens 1982). NDF content of feedstuffs is positively correlated with eating time and rumination and thus may be related to the rate of particle size reduction. NDF is also related to the proper function and health of the rumen. Amount, source, and physical form of dietary NDF is associated with saliva flow, rumen fermentation patterns, milk fat test, and total energy output. Thus, NDF and ADF have been selected as the basis for proposed hay grading standards which are based on laboratory analyses to predict forage quality.

At the recently held meeting of the Hay Marketing Task Force, two major issues were addressed: (1) chemical measures of quality and (2) source of alfalfa (western compared to other areas of the United States). The committee voted to measure percent DM, crude protein, and ADF as indicators of forage quality. When D.A. Rohweder (personal communications) considered five equations for predicting DDM from ADF, the best equation (table 5) did not include western alfalfa. Thus, source of alfalfa appeared to be a factor when chemical assays were used to DDM. Although the Hay Marketing Task Force elected not to use neutral detergent fiber as a predictor of intake, and, thus, not to calculate a relative feed value as initially proposed by the committee (table 4), the Wisconsin researchers will continue development of hay grades based on ADF and NDF values.

Results from several hay auctions held in Wisconsin reveal that the relative feed value (RFV) concept utilizing DDM or dry matter intake evaluated hay more adequately than did CP or ADF alone and the RFV was an effective pricing method.

The correlations between hay price paid and quality factors were:

Factor	R	R^2
RFV	0.76	0.58
ADF	-.70	.49
CP	.53	.28

Animal Response to Forage Quality

To evaluate the proposed market hay grading system, an experiment was designed to determine the change in feeding value of alfalfa with change in maturity and concentrate level using high-producing dairy cows. Alfalfa was harvested at pre-, early, mid- and full-bloom stages of maturity and preserved as dry hay. Chemical composition of the hays met the grades (prime, 1, 2 and 3) proposed in table 3. The

hays were fed to lactating dairy cows which had a previous lactation of over 8,000 kg milk (305 days) and were nearly equal in body weight and age. All cows were between 10 to 12 weeks postpartum and were in positive energy balance at initiation of the experiment. Four trials were conducted using a 4X4 Latin-square design for each stage of forage maturity fed with 20%, 37%, 54%, and 71% concentrate (DM basis). The concentrate contained varying levels of soybean meal to provide isonitrogenously balanced diets. Diets were offered ad libitum, four times daily.

As the level of concentrate feeding increased, digestible dry matter intake increased, regardless of forage maturity. Digestible dry matter intake was highest for diets containing prebloom alfalfa hay at all levels of concentrate feeding.

The correlations between ADF and NDF intakes with digestible dry matter intake were -0.80 and -0.81, respectively. Total chewing time was related to NDF intake, as influenced by forage maturity and concentrate level. As indicated in table 6, a decrease in milk fat test occurred as concentrate level increased for all stages of forage maturity, except for the full bloom hay. Energy output, production of 4% fat-corrected milk (4% FCM), was highest for the prebloom alfalfa hay at all levels of concentrate feeding. However, the highest output of 4% FCM occurred at 54% concentrate for diets containing pre-, early, and mid-bloom alfalfa, while for full-bloom hay, highest 4% FCM output occurred at 71% concentrate. Again, the impact of forage quality can be seen. It is apparent that concentrate feeding cannot substitute for forage quality. Effectiveness of forage fiber (dietary fiber) in maintaining adequate chewing time and rumination, which influence energy output, must be considered as a quality parameter. Cows fed prebloom alfalfa supplemented with 20% concentrate produced more 4% FCM with 20% concentrate (36.2 kg/day) than cows fed full-bloom hay with 71% concentrate (31.6 kg/day). The difference in milk energy output holds even when energy output is corrected for energy from body weight loss for cows fed prebloom hay with 20% concentrate.

Studies by Loosli et al. (1950), Smith (1964), and Collins (1981) indicate that when harvested at the same stages of maturity, red clover and birdsfoot trefoil have a slightly higher nutritive value than alfalfa. Nutritive value differences are due to differences in fiber and lignin concentration. The greater use of alfalfa is due to its greater yield per unit of land and handling qualities.

Use of NDF and ADF in Diet Formulation

Because of the differences in chemical composition of feedstuffs, diets should be formulated on the basis of energy concentration or a measurement such as NDF or ADF which may predict energy value rather than on preconceived forage-to-concentrate ratios. The data of Kawas et al. (1983) (table 6) suggest that during the period of 10 to 26 weeks postpartum, high-producing cows should be fed diets containing less than 32% NDF and less than 22% ADF to maintain a positive weight gain while producing over 30 kg 4% FCM/day. The highest output of 4% FCM occurred with dietary NDF and ADF levels of 24% to 26% and 17% to 21%, respectively. When balancing rations for energy output and weight gain, a minimum dietary level of 28% to 31% NDF and 19% to 21% ADF (DM basis) is suggested for cows between 10 to 26 weeks postpartum. More forage can be used in diet formulation when fiber levels are low. Mertens (1982) suggested diets containing 36% NDF, comprised of different forages and forage-to-concentrate ratios, would support an output of 20 kg 4% FCM. This coincides with the data of Kawas et al. (1983). The level of desired ADF, 19% to 21%, is in agreement with the NRC-Dairy Requirements Cattle (1978). However, cows in early lactation (first 10 weeks) may require a lower dietary ADF level to achieve maximum energy output.

Of total fiber, approximately 80% should come from forage (Jorgensen 1981) which has a mean particle length of at least 1 cm (Santini et al. 1983). However, more data are needed for describing particle size/length of fiber, source of fiber, and amount of fiber before NDF and ADF criteria can be used with assurance in diet formulation.

Future Research Needs

Legumes, especially alfalfa, are the forages of choice in least cost ration formulation. Alfalfa provides the highest returns per unit of land

Table 5 - Regression equations for predicting in vivo dry matter digestibility (Y) from acid detergent fiber (ADF)

Species	Location[1]	Equation	R^2	SD
Alfalfa	E, N, S	1.--Y=89.7-0.806 ADF%	0.67	3.01
Alfalfa	W	2.--Y=52.3-1.97 ADF% + 13.2 ADF%	.64	3.99
All alfalfa		3.--Y=90.2-0.824 ADF%	.65	3.57
All species[2]		4.--Y=92.6-0.878 ADF%	.62	4.11
All species[3]		5.--Y=88.9-0.779 ADF%	.77	2.26

[1]E, east; N, north; S, south; W, west part of United States.
[2]All species, all sources.
[3]All species, does not include W source of forage.

Table 6 - Change in milk fat percentage and yield of 4% fat-corrected milk (4% FCM) as influenced by change in alfalfa maturity and concentrate level

Measurement	Concentrate (% of DM)	Alfalfa maturity (bloom) Pre	Early	Mid	Full
Milk fat (%)	20	3.7	3.3	3.5	3.6
	37	3.8	3.1	3.2	3.6
	54	3.5	3.1	3.1	3.4
	71	3.2	2.9	2.9	3.5
4% FCM (kg/day)	20	36.2	30.9	26.0	23.7
	37	37.8	31.4	28.4	25.2
	54	39.6	35.1	30.1	29.4
	71	39.1	35.1	29.4	31.6

Source: Kawas et al. (1983).

marketed through dairy cattle in many parts of the United States. Future research should emphasize studies on:

1. Maximizing forage utilization.

2. Factors regulating particle reduction.

3. Rate of fermentation.

4. Optimum fiber levels--amount, particle size, and source.

5. Continued development of hay market standards.

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Discussion

Marten: Do you expect birdsfoot trefoil areas to be increased in the United States?

Jorgensen: Yes. At present, it seems to be optimal, but increasing efforts from plant breeders could result in increased acreage. Farmers predict it will survive for 3-10 years; depends on number of harvests per year.

Burns: In the central Northeast, what proportion of dairy cows graze pastures?

Jorgensen: Less than 10% of Wisconsin milk production is from cows that graze for the 120-day summer period. Further, very little green chop forage is fed.

Minson: Are the prices farmers pay at hay auctions related to the grade?

Jorgensen: Yes, to grade and calculated relative feed value.

Rumbaugh: Do you have estimates for dairy cows actually grazing across the United States?

Jorgensen: No. It is greater in the Southeast and is lower as you move to the North Central States. Most of the grazing is on alfalfa, alfalfa-grass mixtures, and some permanent pastures in the North Central States.

Burns: What price level for grain would change farmer-use levels?

Jorgensen: When prices of grain rise, farmers are more careful about balancing their rations, and in fact milk production may rise. If maize prices reach $3.75 or more per bushel, probably the use of forage in rations would increase, with some drop in milk production.

Minson: How widespread is the use of potassium carbonate, and how effective is the machinery used for application?

Jorgensen: It is still mainly at the research level, although there are two products available commercially. Availability of satisfactory application machinery is a major problem.

Nutritional Value of Legumes Preserved as Silage

D.R. Waldo[1]

Abstract

The important substrate characteristics for a good silage fermentation are high dry matter, high sugar or water soluble carbohydrate, low buffering capacity, and the presence of a yeast inhibitor. Legumes have a yeast inhibitor but have a low sugar concentration and a high buffering capacity. Good legume silages are more difficult to make than good grass silages. Ensiling direct-cut legumes without additives will produce silages with extensive protein degradation. Extensive protein degradation will cause low intakes, low production responses, low or negative nitrogen retentions, and decreased protein deposition by ruminants consuming such silages. Good, but variable, legume silages can be made without additives by wilting to about 35% dry matter before ensiling. Properly wilted silages will have protein partially protected from degradation by silage bacteria. These silages are equivalent to, or better than, field-cured hay from the same herbage based on their intake and daily gain or milk production by ruminants consuming them. More consistently, good legume silages could be made by addition of 5 to 6 liters of formic acid per ton of direct-cut herbage. These silages should retain essentially all of the intake and digestibility potential of fresh herbage. The use of an additive that gives protection from protein degradation, such as formaldehyde, should allow utilization of the ample protein of legumes at an efficiency exceeding that of the fresh herbage.

Introduction

Important herbage substrate characteristics are required substrate for a successful clostridia-free, anaerobic silage fermentation. The general characteristics of legumes must be evaluated in relation to these important substrate requirements. Production responses of animals consuming legume silages must be factored into intake, digestibility, and the efficiency of metabolizable energy conversion into maintenance, growth, fattening, and lactation energy. The effect of the silage fermentation on the degradation of protein and its subsequent undegradability by rumen bacteria must be fully appreciated. Efforts must be made to retain, or possibly improve, the high production potential of legumes during silage fermentation.

Principles of Ensiling

Stability Characteristics

An ideal silage fermentation is an anaerobic acid-stabilized fermentation limited by an acidic pH and low water activity that prevent clostridial fermentation. Water activity (a_w) is simply relative humidity (RH) at equilibrium expressed as a proportion; for example, 90% RH = 0.90 a_w (Davis 1980). It is influenced by temperature and solute concentration. Given a particular herbage substrate, a_w is an inverse, curvilinear, monotonic function of the percentage of dry matter (DM). So percentage of DM is a good approximation of a_w for description of herbages. The demarcation line between unstable and stable silages predicts unstable silages at

$$\%DM < 25\ pH - 80 < \%DM$$

for stable silages (Wieringa 1969). Silages at 20% DM are stable when pH is less than 4.0, but silages at 35% DM are stable when pH is less than 4.6.

Herbage Substrate Characteristics

The percentage of DM of the crop at ensiling affects the quality of silage, and the widespread use of wilting before ensiling is a fundamentally sound practice. The major substrate for production of organic acids to reduce the pH in an anaerobic fermentation is sugar (SU) or water-soluble carbohydrate (WSC). Herbage SU or WSC is the major component that affects the acid production potential. Herbage buffering capacity (BC) is the major component that affects the acid required to reach the desired pH. Weissbach et al. (1974) used the ratio of SU/BC and described a demarcation line that predicts unstable silages at

$$\%DM < 45 - 8\ (SU/BC) < \%DM$$

for stable silages, where units for SU are percentage of DM and units for BC are grams of lactic acid/100 g of DM to reach pH 4.0. Wilkinson et al. (1983) challenged the use of the ratio after obtaining greater reduction in variance by considering additive effects of DM, SU, and BC. However, no new parameters were suggested, and no new predictive equation was presented. Another major herbage substrate factor for ensiling is the presence or absence of inhibitors to yeast fermentations.

Legume Substrate Characteristics

The total nonstructural carbohydrates (TNC) of legumes include hexoses, sucrose, and starch as a polysaccharide, but the TNC of temperate grasses include hexoses, sucrose, and fructosan as a polysaccharide (Smith 1973). Fructosan, but not starch, is included in WSC. Fructosan in grasses is a substrate for silage bacteria (McDonald 1981), but malt must be added to hydrolyze starch (Nilsson 1969) before silage bacteria can use it. Thus, the WSC is lower in legumes than in grasses even though the TNC may not be different. Considerable variation exists among the DM, SU, BC, and presence or absence of yeast inhibitors in legumes, grasses, corn, and sorghums. Legumes and grasses are near 20% DM at desired harvest, but corn is near 35% at desired harvest or physiological maturity. The concentration of SU is generally in the order: legumes < grasses < corn. Weissbach et al. (1974) observed the following concentrations of SU: alfalfa, 6.0%; Italian ryegrass, 14.0%; and corn, 23.0% of DM. The BC is generally in the order:

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legumes > grasses > corn. Weissbach et al. (1974) observed the following BC: alfalfa, 7.4; Italian ryegrass, 5.6; and corn, 3.5 g lactic acid/100 g of DM. Using these specific data in the equation of Weissbach et al. (1974) implies that the minimum DM for stable silages is: alfalfa, 39%; Italian ryegrass, 25%; and corn, -8% DM. Legumes and grasses apparently contain an inhibitor of sediment yeast (Olsen and Pedersen 1974), and fermentation to ethanol is inhibited even at low DM content. Corn silages apparently do not contain an inhibitor, and ethanol concentrations in corn silage are inversely related to its percentage DM (Andrieu 1976). The production of ethanol becomes a factor when corn is ensiled at less than 35% DM, and this is a major reason that corn silages with DM at less than 35% are less successful. Presumably, yeast fermentations and alcohol production, rather than acid production, account for the extensive DM losses observed for ensiled sweet sorghum (Ramsey et al. 1961). The greater accumulation of nonstructural polysaccharide as starch rather than fructosan in legumes makes the ensiling of legumes more difficult than is the ensiling of grasses. Legumes have the yeast inhibitor but have the most unfavorable S and BC of any major ensiled forage class.

Efficiency of Fermentation

The model of Weissbach et al. (1974) does not consider differences in the efficiency of converting sugar to hydrogen ions. The type of fermentation affects the efficiency of producing hydrogen ions (table 1) as well as the recovery of energy and dry matter (McDonald et al. 1973, Owens and Prigge 1975, McDonald 1981). Hexoses are converted to only lactic acid in homolactic fermentations, but they are converted to mixtures of lactic and acetic acids plus ethanol and mannitol in heterolactic fermentations. Pentoses are converted to mixtures of lactic and acetic acids in heterolactic fermentations. Clostridial fermentations produce butyric acid from glucose; they can also convert two moles of lactic acid to one mole of butyric acid, which considerably reduces hydrogen ions. A yeast fermentation of glucose produces ethanol, which contributes essentially no hydrogen ions. The type of fermentation makes a very large difference in the quantity of hydrogen ions produced per mole of hexose or pentose. Recovery of energy from fermented sugars is 0.95 or better, except for the clostridial fermentations where it drops to about 0.82. Recovery of dry matter from fermented sugars ranges from 1.00 for homolactic fermentation of glucose, 0.76 for heterolactic fermentation of glucose, and 0.49 for clostridial fermentation of glucose. Dry matter recovery slightly overestimates energy recovery for a homolactic glucose fermentation, but dry matter recovery is only slightly more than one-half of energy recovery for a yeast fermentation of glucose.

Table 1 - Hydrogen ion production plus energy and dry matter recovery from silage fermentations[1]

Fermentation type	Moles substrate	Moles product	pK generated[2]	Recovery	
				Energy	Dry matter
Homolactic	1 Hexose	2 Lactic acid	2.76	0.99	1.00
Heterolactic	1 Pentose	1 Lactic acid 1 Acetic acid	1.56	.95	1.00
Heterolactic	1 Glucose	1 Lactic acid 1 Ethanol	1.38	.98	.76
Heterolactic	3 Fructose	1 Lactic acid 1 Acetic acid 2 Mannitol	.518	.99	.95
Clostridial	1 Glucose	1 Butyric acid	.148	.82	.49
Clostridial	2 Lactic	1 Butyric acid	.148	.82	.49
Yeast	1 Glucose	2 Ethanol	nil	1.00	.51

[1]Adapted from McDonald et al. (1973), McDonald (1981) and Owens and Prigge (1975).

[2]Summation of moles of product x dissociation constant of product x 10^{-4} from one mole of original monosaccharide as calculated by author.

Protein Preservation

Clostridial fermentation and protein degradation are generally reduced by ensiling relatively dry materials. The regression equation derived from the data of Hawkins et al. (1970) for alfalfa is

$$Y = 23.6 + 0.63 X,$$

where Y = insoluble nitrogen as a percentage of total nitrogen, and X = % DM in silage. Similar direct relationships between insoluble nitrogen and dry matter have been observed for corn silages (Wilkinson 1976) and ensiled high-moisture corn grain (Sprague and Breniman 1969, Thornton 1976). The protection of protein from degradation by silage bacteria will make a better feed for high-producing ruminants and should receive more emphasis as a criterion of good ensiling. Silages are capable of supplying the ruminant with a protein that may range from highly degradable to highly undegradable by rumen bacteria (ARC 1980).

Animal Responses to Legume Silages

Production

Legume silages can give animal production responses that range from very poor to very good. Cattle fed five untreated direct-cut alfalfa silages gained only 60 g/day (Lancaster et al. 1977). Holstein heifers or steers weighing about 300 kg were fed seven direct-cut alfalfa silages cut in 5 years that were treated with mixtures of formic acid and formaldehyde; these silages produced a mean gain of 963 g/day (Waldo and Tyrrell 1983; H.K. Goering et al., unpublished data; D.J. Thomson et al., unpublished data; D.R. Waldo, unpublished data). Lactating cattle, each fed 7 kg concentrate DM daily, produced more milk, milk protein, and lactose when they were fed red clover silage compared with perennial ryegrass silage (Thomas et al. 1982), but milk fat and total solids production did not differ. Differences in milk production did not persist when all cows were switched to perennial ryegrass silage at 12 weeks.

Intake

The potential intake of fresh herbages can be markedly decreased by improper ensiling technique (Waldo and Jorgensen 1981). But with good ensiling technique, seven grass silages prepared with formic acid were consumed by heifers at 98% of the intake of fresh herbage (Dulphy and Michalet 1977). Well-preserved legume silages should be consumed at nearly 100% of the potential of the fresh herbage. The daily DM intake of four direct-cut alfalfa silages treated with mixtures of formic acid and formaldehyde was 102 g/kg$^{0.75}$ compared to 77 g/kg$^{0.75}$ for four orchardgrass silages; intake was primarily a function of cell-wall contents (H.K. Goering et al., unpublished data; D.J. Thomson et al., unpublished data). Similar proportional differences were observed for the intake of two red clover silages relative to two perennial ryegrass silages (Thomas et al. 1981). The withdrawal of barley from the diet increased the intake of red clover silage more than the intake of perennial ryegrass silage. Lactating cows, each fed a constant 7 kg of concentrate DM daily, consumed more red clover than perennial ryegrass silage DM (Thomas et al. 1982).

Digestibility

Digestibility is less affected by ensiling technique than is intake (Waldo and Jorgensen 1981) if the effects of extensive heat damage that results either from ensiling material that is too dry or from ensiling too slowly are avoided. Four alfalfa silages prepared with mixtures of formic acid and formaldehyde had energy digestibilities of 59%; four orchardgrass silages harvested at the same time and prepared similarly had energy digestibilities of 57% (H.F. Tyrrell et al., unpublished data). Thomas et al. (1981) found no difference between organic matter (OM) digestibilities for perennial ryegrass and red clover silages, but OM digestibility decreased more rapidly with delayed harvest for perennial ryegrass silages than for red clover silages.

Energetic Efficiency

Limited data are available on the efficiency of utilization of metabolizable energy in silages. Thomas and Chamberlain (1982) found that the observed efficiency for maintenance (k_m) agreed with calculated values, but the observed efficiency for fattening (k_f) was very variable relative to calculated values when grass silages were fed without supplemental concentrate. Supplementation with concentrate increased the predictability of k_f. They originally thought that this inefficiency was caused by D-lactic acid but now feel the cause is unexplained. The inefficiency may be caused by destruction of protein during the silage fermentation and insufficient amino acids being available for digestion and absorption to meet the physiological potential of the test animal. Calorimetric studies at Beltsville have not detected significant differences in retained energy when equalized intake energy was supplied by orchardgrass (Waldo and Tyrrell 1980) or alfalfa (Waldo and Tyrrell 1983) that was fed as direct-cut silage either untreated or treated with formic acid and formaldehyde. H.F. Tyrrell et al. (unpublished data) have calculated the energetic efficiency for alfalfa silages to be greater than the energetic efficiency for orchardgrass silages.

Protein Utilization

Extensive protein degradation during the fermentation of untreated direct-cut alfalfa silages can produce negative nitrogen balances (Durand et al. 1968) and live-weight losses (Joyce and Brunswick 1975). Alfalfa silage wilted to 47% DM contained 23% undegradable N, and alfalfa hay contained 25% undegradable N when fed to sheep (Merchen and Satter 1983a). Alfalfa silages wilted to 29%, 40%, and 66% DM contained 15%, 15%, and 36% undegradable N, respectively, and alfalfa hay contained 22% undegradable N when fed to cattle (Merchen and Satter 1983b). Feeding direct-cut alfalfa silages treated with formic acid and formaldehyde to Holstein steers weighing about 300 kg produced nitrogen (N) retentions of 40 g/day by N-balance technique or protein depositions equivalent to 25 g of N/day by slaughter-balance technique (Waldo and Tyrrell 1983). These values were not increased by feeding a formaldehyde-protected casein supplement. Proper ensiling of legumes should increase undegradable N and maintain a high apparent digestibility of N in the small intestine. Siddons et al. (1979) prepared perennial ryegrass silage with formic acid and formaldehyde and increased ruminally undegraded protein from 17%

to 67% and maintained the apparent digestibility of protein in the small intestine at 57%. Untreated direct-cut legume silages usually promote very low N utilization. Wilted legume silages are widely used in the United States, are subject to variable weather during wilting, have variable percentage DM at ensiling, and have variable N utilization. Dulphy (1980) proposed the use of direct-cut legume silages with 5 to 6 liters of formic acid per metric ton added at ensiling as a positive control or reference silage. The use of some other additive that has the effects of formaldehyde for protecting protein from silage bacteria and rumen bacteria should allow the range of ruminal undegradability observed by Siddons et al. (1979). Controlled protection of protein through ensiling seems to offer the most promise of fully using the high protein concentration of legumes for high production from ruminants.

Research Needs

Economical and safe methods of protecting proteins against degradation in the ensiling process or in haymaking are needed. Repeatable systems for supplying the high-producing ruminant with legume proteins that are 35% to 50% undegraded in the rumen are needed. Formaldehyde will do this economically, but is not considered safe in many countries. Wilting of legumes before ensiling will not produce legume proteins that are undegradable enough, plus the control of the extent of wilting and subsequent undegradability will be too variable. Even field-cured hay needs to have more undegradable protein for feeding the high-producing ruminant.

The potential for breeding legumes with slightly higher tannin contents to reduce protein undegradability needs to be investigated. This approach would presumably reduce the undegradability of legumes whether grazed or stored as either silage or hay.

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Discussion

Marten: Is grass treated with formaldehyde and formic acid not a sterilized product rather than a silage?

Waldo: No, there is still plenty of fermentation. If there was enough formaldehyde and formic acid to sterilize the forage, there would not be much digestion in the rumen.

Barry: Agreed. At the levels of treatment recommended, there is no adverse effect on fermentation.

Barry: Formalin/formic acid mixtures have been around experimentally for about 10 years. What is the adoption in the United States?

Waldo: They have not been approved for use in the United States.

Brougham: Are you involved in extension? Someone with this knowledge of silage would be helpful moving amongst N.Z. farmers, speaking of silage generally, not just treatment with formaldehyde.

Waldo: No. I can see no economically viable alternative to formaldehyde, for protecting forage protein for degradation during the silage fermentation process.

Barry: In New Zealand, lack of commercial interest in supplying the product has inhibited farmer use. There is an unfortunate lack of interest in silage in some quarters of the extension/research system.

Minson: Could you explain the difference between calorific and slaughter results?

Waldo: Differences may occur for N and energy measurements between calorimetric and slaughter balance data. Using N-balance techniques, it is possible to get losses during sample collection. Calorimetric measurements are made in the absence of exercise and at a thermoneutral temperature. It is considered important to obtain transfer coefficients so that results from different methods can be compared and fully used in the development of feeding standards.

Jorgensen: Is the 38% increase in the metabolizable energy for growth you mention as a fat-free tissue?

Waldo: No, it is a 38% increase in total tissue energy deposited relative to the metabolizable energy available for growth.

Wet Fractionation of Legume Forages

Neal A. Jorgensen and Chris D. Lu[1]

Abstract

Wet fractionation of green plants is a process which divides plant tissue into three major fractions: (1) pressed forage, (2) protein concentrate, and (3) deproteinized juice. The process involves direct harvest followed by cell rupture or maceration and juice expression. This yields a pressed forage and a raw juice. The pressed forage can be fed fresh, ensiled, or dehydrated. Separation of protein concentrate from the juice is usually by heat coagulation or acid treatment. The protein concentrate can be preserved in wet or dried forms and can be an excellent feed or food for all classes of animals. The deproteinized juice may be used as a fertilizer, medium for single-cell production, or added to the pressed forage before dehydration. The process can increase utilization of forage nutrients.

Introduction

Wet fractionation is a process in which juice is expressed from freshly cut herbage which is normally at a relatively early stage of maturity. The liquid fraction represents about half of the fresh crop weight and contains 7% to 10% dry matter. This amounts to 20% to 25% of the total crop dry matter and might contain up to 33% of the crude protein in the crop. The resulting solid or fibrous fraction usually varies in moisture content from 65% to 75% and has an average particle size considerably smaller than that of the initial crop. The liquid fraction is occasionally used in its entirety either fresh or preserved. More frequently, however, it is further divided into a high-protein fraction containing 40% to 60% crude protein on a dry matter basis and a deproteinized juice fraction with 7% or less dry matter and negligible true protein content. The fibrous fraction is almost always used for ruminants and may be fed fresh, ensiled, or dehydrated.

Reasons for Using the System

There are several advantages associated with the wet fractionation process. These include: (1) reduction in field losses, (2) increased weather independence of the harvesting process, and (3) increased flexibility of product utilization.

Production

Since the reasons for carrying out the wet fractionation process vary considerably, there are a number of variations in the process, including:

1. Plant species
2. Scale of operation; from less than 50 kg/h to more than 40 tonnes/h
3. Location of operation; field, farmstead, or centralized processing plant
4. Types of equipment and methods used for the various subprocesses
5. Priorities; maximize protein concentrate production or maximize forage quality
6. Use and form of end products and method of preservation

One processing pathway and the approximate weights of the various fractions was presented by Ream et al. (1983). Other pathways are described by Pirie (1978) and Telek and Graham (1983).

Despite the diversity in the wet fractionation process, the freshly cut herbage generally undergoes four major steps:

1. Cell rupture, also referred to as "maceration" or "pulping"
2. Juice expression
3. Separation of protein concentrate from the juice fraction
4. Preservation and storage of products

Cell Rupture

While cell rupture and juice expression are sometimes carried out concurrently in such devices as roll presses and screwpresses, the dissimilarity in requirements of the two processes leads to less efficient use of equipment and energy.

Cell walls can be ruptured by subjecting them to a sufficiently high level of force imbalance across individual cells. A cell rupture device was developed at the University of Wisconsin which creates the necessary force imbalance by extruding the herbage through orifices (Nelson et al. 1983). This concept was developed into a continuous rotary machine by the use of a cylindrical rotating orifice ring with a cylindrical roller running on its internal surface to extrude herbage radially outward through the orifices. This design was built in various sizes, the largest of which had a crop throughput in excess of 20 tonnes/h while requiring less than 1.6 kw-h/tonne.

Evaluating the actual percentage of cells ruptured in a large quantity of herbage by a given process is a desirable, but challenging task. Emetarom and Barrington (1977) proposed washing a representative sample of processed herbage under prescribed conditions. This wash water is then filtered, and the electrical conductivity of the filtrate is determined. This filtrate conductivity is then compared with that from the same herbage, which was subjected to a standard treatment, that is, 2 minutes in a Waring blender. While this procedure does not

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determine the percentage of cells ruptured, it does yield an index to indicate the relative effectiveness of a given process.

Expression of Juice

A mass of herbage which has undergone a cell rupture process contains a certain volume of solids and a certain volume of voids which are occupied by both liquid and gas. The solids and the liquid are essentially incompressible. Expression of juice requires that the mass be compressed until the volume of voids is reduced to less than the volume of the liquid contained in them. A rough requirement for the expression of enough juice to reduce the herbage from a moisture content of 80% wet basis to 67% wet basis (liquid:solid ratio reduced from 4:1 to 2:1) is that a pressure of at least 700 kPa be maintained for more than 1 minute. A lower pressure can be partially compensated for by a longer holding time, or a shorter holding time can be partially compensated for by a higher pressure. The time rate of juice expression can be increased somewhat by reorientation of the material while it is compressed. This is done at the cost of an increased energy input.

The most commonly used press for forage fractionation is the screw press. These may be single or double screw presses. Roll presses and belt presses have been used but were developed for pressing sugarcane.

A "cone" or "vee" press for forage fractionation was designed, constructed, and evaluated at the University of Wisconsin (Straub and Koegel 1983). This rotary press has two opposing pressing surfaces in the form of rather flat cones whose axes intersect at the cone vertices, but are slightly nonparallel. The nonparallel axes cause the cone surface to have a minimum spacing and a maximum spacing between them at location 180° apart. The herbage is packed between the cones at the maximum spacing, travels, and is compressed between the slowly rotating cones for 180° of rotation until the minimum spacing of "NIP" is reached and is then removed from between the cones by a stationary plow. The cone press evaluated could reduce the moisture in 12-15 tonne/h of alfalfa herbage from 80% to 65% w.b. when rotated at 0.3 r/min. The energy requirement did not exceed 1.5 kw-h/tonne.

Protein Separation

The protein fraction of the juice is usually separated by means of coagulation. Membrane technology has also been used experimentally. Coagulation may be accomplished by the addition of heat or by lowering the pH to below 4.5. The latter may be accomplished either by the addition of acid or by the production of acid during anaerobic fermentation of the juice.

Heat coagulation is frequently accomplished by the injection of steam into the juice. When fresh alfalfa juice is heated, the coagulated protein floats to the surface and may be separated by skimming or straining. Since the protein molecules have a greater density than the juice, the flotation appears to be made possible by naturally occurring gas bubbles adhering to the coagulated protein. The protein concentrate obtained by skimming or straining usually has a moisture content between 85% and 90%. More than half of this liquid can be removed by pressing (Straub and Bruhn 1978). Kohler et al. (1983) and others have used a decanter centrifuge to separate heat-coagulated protein from juice. They have achieved solid contents as high as 50% by this method. When too much time elapses between cutting and processing, the effectiveness of the heat coagulation/flotation process suffers. This may be due to proteolysis and other related changes in the juice. Two hours is probably the maximum allowable time between cutting and processing.

The quantities of various acids required to lower the pH of alfalfa juice sufficiently to precipitate the protein was studied by Ajibola et al (1982). Ajibola et al. (1981) also studied the autofermentation of alfalfa juice as a protein precipitation technique. They found that the variable-length lag phase preceding fermentation could be eliminated by adding 5% by volume of the supernatant from the previous day's fermentation. In so doing, the pH was lowered to the desired level of 4.5 within 24 hours at ambient temperature. Increasing the temperature further reduced this time. The final pH achieved was determined by the nonstructional carbohydrate content of the juice. If carbohydrate content was insufficient to lower the pH to the level desired, this could be accomplished by addition of a carbohydrate source to the juice.

After precipitation, it is possible to decant approximately 67% of the juice volume. The precipitate thus obtained is much finer grained than heat-coagulated protein and is thus more difficult to further dewater by pressing or centrifugation. It can, however, be resolubilized by pH adjustment if this is desired, whereas heat-coagulated protein is irreversibly denatured.

Protein Preservation

Preservation of the protein concentrate can be accomplished by dehydration, chemical preservatives, or by mixing it with grain to create a high-energy/high-protein supplement which is stored under anaerobic conditions. Dehydration can be accomplished in spray dryers, drum dryers, or by forming the partially dewatered concentrate into pellets and passing heater air through it. Propionic acid was found to be an effective preservative in concentrations above 1.5% (Straub et al. 1982). This method may be particularly attractive where protein concentrate must be held for several months until it can be mixed with grain for final storage under anaerobic conditions.

Deproteinized Juice

The deproteinized juice can be used as a liquid fertilizer or as a culture medium for single cell organisms, or it can be concentrated or dried along with the pressed forage fraction for feed use.

Utilization

Pressed Forage

Pressed forage, the high-fiber fraction that remains after pressure fractionation, may be fed and/or stored as fresh, ensiled, or dried material (Telek and Graham 1983).

The fiber components are increased in the forage fraction as a result of the wet fractionation process (table 1). Thus, it is reasonable to assume dry matter intake and digestibility of pressed forage would be lower than that of the original plant material. However, quality was not reduced to the extent expected (Lu et al. 1982b). This is attributed to perturbation caused by the mechanical force during the wet fractionation process. Since application of mechanical force causes disruption of the cellular structure of plant tissue, the degree of crystallinity or rigidity of physical barriers is reduced. Consequently, part of the fiber fraction not usually available for bacterial degradation becomes available (table 2). This counterbalances the depression in dry matter intake and digestibility caused by removal of cell solubles. Digestibility of fiber components is increased by both cell maceration and pressure fractionation (Lu et al. 1982b). Compared to direct-cut hay, pressed hay is about equal in feeding value for milk production and weight gain in ruminants (Connell and Cramp 1975).

Fermentation pattern has a critical influence on the utilization of pressed silage by ruminants. Reduction in moisture content, removal of nonstructural carbohydrate or cell contents, and disruption of plant cell walls are the three major factors affecting fermentation of ensiled pressed forages. The extent of fermentation is expected to be reduced as a result of moisture reduction and the removal of cell contents. On the other hand, the extent of fermentation is enhanced by the disruption of plant cell walls. Therefore, the extent and pattern of fermentation in pressed silage is determined by the extent of reduction and

Table 1 - Mean composition of alfalfa silages[1]

	Russell et al. (1978)		Lu et al. (1979)	
	Wilted	Pressed	Wilted	FPS
Dry matter (%)	42.1	30.5	46.4	30.2
% of dry matter (DM):				
Crude protein	18.5	15.9	23.3	16.8
Neutral detergent fiber	47.2	57.8	40.4	54.6
Acid detergent fiber	37.6	47.4	30.7	39.0
Organic acids, % of DM:				
Acetic	2.1	3.8	1.5	1.0
Propionic	.2	.5	.1	.1
Butyric	.1	1.2	.1	.1
Lactic	3.8	2.7	4.6	3.5
Total	6.2	8.2	6.2	4.6
% of total N:				
Nonprotein N	20.4	27.2	45.0	34.0
Ammonia N	8.6	3.2	7.2	3.8

[1]Wilted = total forage cut and field wilted, FPS = pressed forage treated with 0.5% formic acid (wt/wt).

Source: Russell et al. (1978) JAS, with approval of American Society of Animal Science; Lu et al. (1979) JDS, with approval of American Dairy Science Association.

Table 2 - Mean apparent digestibility of alfalfa silages[1]

	Digestibility (%)			
	Russell et al. (1978)		Lu et al. (1979)	
Measurement	Control	Pressed	Control	FPS
Dry matter	62.8	61.9	67.1	66.3
Crude protein	71.1	71.2	76.5	71.9
Neutral detergent fiber (NDF)	58.2	59.4	59.3	62.8
Acid detergent fiber (ADF)	56.4	55.4	57.2	58.6
Hemicellulose (NDF-ADF)	72.1	75.7	57.4	69.4
Cellulose	60.7	62.3	68.1	69.8

[1]Silages: Control, total forage field wilted; FPS, formic-acid treated pressed silage.

Source: Russell et al. (1978) JAS, with approval of American Society of Animal Science; Lu et al. (1979) JDS, with approval of American Dairy Science Association.

enhancement which reflects the amount of moisture and cell contents being removed and the number of cells being disrupted. This partially explains the inconsistency of results regarding quality of pressed silage reported by research groups (Raymond and Harris 1957, Derbyshire et al. 1969, Oelshlegel et al. 1969, Vartha et al. 1973, Russell et al. 1978). Cell maceration enhances the extent of fermentation, and pressure fractionation reduces the extent of fermentation (Lu et al. 1982b). Compared to unwilted silage, pressed silage appears to be of better quality due to a more desirable fermentation pattern and a higher intake and digestibility by ruminants (Vartha et al. 1973). However, a lower dry matter intake was reported in animals fed pressed silage compared to wilted silage (Derbyshire et al. 1969, Russell et al. 1978). Dairy cows fed pressed silage produced slightly less or the same level of milk as those fed wilted silage. Undesirable fermentation pattern in pressed silage as evidenced by high concentrations of ammonia nitrogen and volatile organic acids was related to the lower dry matter intake (Russell et al. 1978, Lu et al. 1982b). Higher moisture content than conventional wilted silage and/or the disruption of cell walls are the two main factors contributing to undesirable fermentation in pressed silage (table 1). Extracting more juice from green plants in order to reduce moisture and consequently improve the condition for ensiling has not been successful. Reducing moisture by double pressing depressed dry matter intake and digestibility. This was due to removal of large quantities of readily digestible nutrients (Lu et al. 1982b).

Utilization of pressed silage treated with formic acid is equal to that of conventionally wilted silage (table 3). Through the addition of formic acid, both preservation characteristics and animal productive performance were improved compared with untreated pressed silage (Lu et al. 1979). Formic acid treatment depressed ammonia nitrogen, nonprotein nitrogen, total volatile fatty acids, and acetic acid and increased lactic acid content of the pressed silage (Lu et al. 1979). Chemical modification to improve ensiling condition has provided a method for making pressed silage competitive with high-quality conventionally wilted silage.

Protein Concentrate

Chloroplastic and cytoplasmic proteins represent two major extractable fractions from green plants (table 4). The proteins can be coagulated and separated from deproteinized juice. Chloroplastic protein is precipitated from raw juice when heated at 50° to 55° C. Cytoplasmic protein is the fraction obtained from reprecipitation of the supernatant fraction by heating at 80° C or higher. The procedure for fractionating the whole protein into cytoplasmic and chloroplastic proteins has not been standardized among research groups, and the terminology is loosely used. Protein concentrate will be referred to as whole protein in this section.

Processing conditions are likely to be the most important factors affecting quality of protein concentrates. Numerous chemical reactions, both enzymatic and nonenzymatic, can occur after the green plant is harvested. Composition of protein concentrate, which ultimately dictates quality, is influenced by the end products of these reactions. Under conditions found in raw juice, which provides a favorable condition for proteolysis to occur, true protein can be converted to nonprotein nitrogen. Consequently, both the extractability and quality of protein are reduced. Nonenzymatic reactions such as the reactions between phenolic compounds and amino acids in extracted protein will reduce availability of amino acids (Van Sumere et al. 1975, Fatunso and Byers 1977).

Table 3 - Mean response of cows fed wilted silage (control) or pressed silage treated with formic acid (FPS)[1]

Measure	Control	FPS
Dry matter intake:		
Silage (kg/day)	10.5	13.3
Concentrate (kg/day)	7.1	7.1
Total (kg/day)	17.6	20.4
Production:		
Milk (kg/day)	21.9	22.8
Fat (%)	4.1	4.0
4% FCM (kg/day)	22.7	22.8
Protein (%)	3.4	3.5

[1]Control, 46.4% dry matter; FPS, 30.2% dry matter, treated with 0.5% (wt/wt) formic acid.

[2]4% FCM = 4% fat-corrected milk.

Source: Lu et al. (1979) JDS, with approval of American Dairy Science Association.

The wet fractionation of alfalfa can provide nonruminants with a protein source that is unavailable conventionally. The utilization of protein concentrate by ruminants is important if the wet fractionation process is to be considered as an on-the-farm process. Production and utilization of protein concentrate would allow farmers to redistribute forage proteins and thus reduce cost of purchased protein supplements. Extent of protein degradation is important in determining the value of protein sources for ruminants. A protein source that provides optimal ruminal microbial protein synthesis while allowing maximum escape from ruminal degradation followed by intestinal absorption may be considered as an ideal protein source for ruminants if that which escapes the rumen is of high biological value. Substantial evidence suggests that the rate and extent of ruminal degradation of alfalfa protein concentrate can be altered by processing conditions (Lu et al. 1981, Lu et al. 1982a). Alfalfa protein concentrate coagulated by heat at 80° C is more resistant to microbial degradation in the rumen than that coagulated at 60° C. Depending upon the processing condition, ruminal degradability of alfalfa protein concentrate ranges from 51% to 74% (Lu et al. 1982b). Regression analysis revealed that degradability of alfalfa protein concentrate was 56% (Lu et al. 1982a). Apparent absorption of nitrogen in the small intestine ranged from 66% to 70% for alfalfa protein concentrate. The rate of amino acid absorption in the small intestine ranged from 71% to 81% (Lu et al. 1982a, Lu et al. 1983b). In a comparison to soybean meal, alfalfa protein concentrate appeared to be more resistant to ruminal degradation and was well utilized by lactating dairy cows (Lu et al. 1983c).

High concentrations of saponin in the diet affect microbial fermentation (Lu et al. 1983d). Evidence supports the speculation that ruminants are less sensitive to undesirable compounds in leaf protein concentrate, such as saponins and polyphenols, than are nonruminants (Jayasuriya et al. 1982). Quality of protein and the association of antiquality substances with leaf protein concentrates represent two major concerns in the utilization of these proteins by nonruminants and poultry. Addition of methionine and lysine improved the utilization of leaf protein concentrates by rats and chicks. Alfalfa protein concentrate is comparable in amino acid composition to the major plant protein sources, such as soybean meal. Substantial evidence suggests that availability rather than composition is the major factor affecting quality of leaf proteins. Reduction in lysine availability is related to undesirable processing conditions during coagulation and dehydration (Walker 1979a, 1979b). A time delay between extraction and coagulation can result in oxidation of methionine, thereby reducing availability of methionine. Availability of S-containing amino acids and lysine is reduced as a result of processing conditions which favor reactions between phenolic compounds and amino acids (Mcleod 1974, Fatunso and Byers 1977).

Table 4 - Composition of alfalfa protein concentrates

	% Dry matter basis				
Protein concentrate	Crude protein	Ether extract	Crude fiber	Ash	Nitrogen-free extract
Whole	46-62	6-9	1-3	10-12	14-17
Chloroplastic (green)	38-46	11-14	4-6	14-16	20-22
Cytoplasmic (white)	82-91	.4-.7	.5-1	.3-.5	8-10

Source: University of Wisconsin Plant Juice Protein Team.

Antiquality substances such as saponins, estrogenic flavonoid compounds, phenolic compounds, and alkaloids are critical to the utilization of leaf protein by nonruminants. Feeding alfalfa protein concentrate prepared from high saponin strains retards growth of poultry, swine, rabbits, and rats (Tung et al. 1977, Cheeke et al. 1977, Hegsted and Linkswiler 1980). Coumestrol, one of the estrogenic flavonoid compounds, precipitates with leaf protein concentrate during coagulation (Knuckles et al. 1976). Estrogenic flavonoid compound can interact competitively with natural estrogens in animals. Phenolic compounds are known to interfere with protein extraction and reduce the availability of amino acids. Precautions need to be taken to prevent the contamination of leaf protein concentrates with antiquality substances. Protein concentrate prepared by anaerobic fermentation may contain less toxic material than that prepared by heat coagulation. It is possible that leaf protein concentrate prepared by anaerobic fermentation may be better utilized by nonruminants. However, the loss of protein due to the conversion of protein to nonprotein nitrogen during fermentation should not be overlooked (Lu et al. 1982b).

Consumption of leaf protein concentrate by human subjects was reviewed (Pirie 1978). It is clear that leaf protein concentrate cannot substitute completely for milk. However, leaf protein has a potential to improve the health of malnourished children, especially in underdeveloped areas. When compared to values suggested by FAO, amino acid composition of leaf protein is good. Cytoplasmic protein prepared from alfalfa is comparable to casein in essential amino acid composition (Lu 1981). Recent studies suggest that soluble alfalfa protein can be prepared to serve as an ingredient for human food (Knuckles and Kohler 1982). Consumption of leaf protein or fractions of leaf protein will be expanded, provided continuing research efforts are undertaken.

Deproteinized Juice

Deproteinized alfalfa juice contains nonstructural carbohydrates, nonprotein nitrogen, potassium, phosphorus and other minerals. Deproteinized juice may be used as a medium for single cell protein production or as a fertilizer (Telek and Graham 1983). It may not be feasible to feed deproteinized juice to animals due to the existence of antiquality substances and low dry matter content. However, high moisture and nonstructural carbohydrates make it a potential medium for production of biomass. Substantial amounts of biomass can be produced from anaerobic fermentation of deproteinized juice (Beker et al. 1979). Yield of single cell protein can be increased by the addition of nitrogen and phosphorus to deproteinized juice. Deproteinized juice can be used as a fertilizer due to its nutrient content. Application of deproteinized juice to alfalfa fields stimulates regrowth. Using deproteinized juice as a fertilizer is important if the concept of an on-the-farm process is adopted.

Future Research Needs

Development of an on-the-farm process will require continued research in areas of:

1. Development of processing equipment that is energy efficient and low cost
2. Removal of antiquality factors
3. Preservation of protein concentrate
4. Processing of the deproteinized juice

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Discussion

Easton: Are humans affected by saponin?

Jorgensen: The areas where leaf protein concentrates are being used for human nutrition, alfalfa is not being used. By fractionation of the protein, a product (white protein) can be produced that is acceptable.

Minson: The greatest opportunity for the use of the process would appear to be in the tropics. However, crude protein levels in tropical forages are normally less than 15%, which would appear to be too low for the extraction process.

Jorgensen: Yes, these levels will be too low for the process to be efficient.

Barry: If energy for drying down is a limiting factor, can the high-protein juice be fed directly to, say, pigs?

Jorgensen: This has been researched. The use of liquid products has problems with extremes of temperature. The juice fed to pigs works well, but oxygen must be kept out if the product is not to putrefy, and this is difficult. We have had no success in finding an economical chemical stabilizer.

Marten: What is the feasibility of converting low saponin alfalfa to protein concentrate?

Rumbaugh: Saponin levels can be reduced by a simple procedure and recycling populations a number of times. It could be done without losing any of the adaptive characteristics of the cultivars.

Field: There is a plant in New Zealand. Its main aim is to sell a pigment carrier.

Barry: The main interest in the N.Z. plant is in selling as a pigment source.

Easton: However, they are trying to separate the white protein as a separate product, leaving green deproteinized product as a pigment source.

Jorgensen: The pigment levels are such that the products can be added to poultry rations at low enough levels that antiquality factors are of no real problem.

Regulation of Forage Intake in Ruminants

D.R. Waldo[1]

Abstract

Regulation of intake in ruminants is primarily a function of physical fill for diets that are energetically bulky and less digestible, such as high-forage diets; but intake becomes primarily a function of metabolic control for diets that are energetically dense and highly digestible, such as high-concentrate diets. Physical limitation of pure forage diets fed to growing ruminants is generally considered to be unpassed and undigested residue in the rumen. However, the physical limitation of forage-concentrate diets of low digestibility fed to lactating cows is implied to be fecal production of undigested residue. Cell-wall concentration of forage diets is the best single chemical predictor of intake. Gastrointestinal-tract fill is important because it can cause a physical, or volume, limitation to intake; a difference in energy concentration of weight gain; and a potential difference in energetic efficiency. Prediction of intake is less precise than the prediction of digestibility or energetic efficiency. Intake of forages fed with concentrates is best considered as a curved response surface that is functionally related to the amount, or ratio, of concentrate fed and is continuous with the intake of forages fed alone. Depression of dry-matter digestibility associated with increased intake is less for legumes than for grasses.

Introduction

Primary factors in the conversion of forage to animal product are intake of dry matter (DMI) or energy (IE), digestibility, efficiency of converting digested energy to metabolizable energy, and efficiency of converting metabolizable energy to net energy in animal product. Relative contributions to differences in digestible DMI were 70% for intake and 30% for digestibility when both grasses and legumes were included (Crampton et al. 1960). Anderson et al. (1973) apportioned differences in digestible DMI of alfalfa to intake, 47%; digestibility, 26%; and combined, or inseparably correlated, effect, 27%. Intake is generally more important than digestibility, and the importance of intake relative to digestibility increases as more diverse species are included in the data set. The estimation of either intake or digestibility of forage by an animal includes both forage and animal components of variation. The animal component is larger relative to the forage component for estimation of intake than for estimation of digestibility. This means that investigators must describe the physiological state of animals, use standard animals, or reference intakes of unknown forages to intakes of standard forages. Ultimately, prediction of intake must consider animal variation as well as forage variation.

Units for Describing Intake

Fundamentally, a unit of intake would factor out only intake per se and not include other factors in the description of conversion, such as digestibility. A commonly used unit is DMI as a percentage of body weight (W) which implies $W^{1.00}$. A second common unit is DMI relative to $W^{0.75}$. Use of $W^{0.75}$ provides a direct relation to most energy systems used today. Colburn and Evans (1968) found $W^{0.54}$ to be more highly correlated with forage intake by growing steers of different sizes. Poppi et al. (1980) used $W^{0.90}$ to minimize variance between sheep and cattle. Units of intake that include other factors, such as digestibility, are also used to compare intake of productive energy because it is important economically and practically. For example, much of the literature on intake in relation to digestibility depression (Tyrrell and Moe 1975) uses multiples of maintenance; a multiple of maintenance includes digestibility.

Regulation of Intake

Regulation of intake in ruminants is under control of one of two systems depending upon dietary characteristics. Intake of energetically dense and more digestible diets is primarily under metabolic control, or is limited to nutritional need, in the animal. Intake of energetically less dense and less digestible diets, such as forages, is primarily under physical control, or is limited by the space occupied within the gastrointestinal (GI) tract. Conrad et al. (1964) developed a model to predict the intake of forage-concentrate diets by lactating cows. Intake increased as digestibility increased to maintain a fecal dry matter (DM) output of about 1.07% of body weight until a cow satisfied her energy requirement. The constant fecal output relative to body weight at lower digestibilities implies a physical limitation in the lower intestine. Intake of more digestible diets decreased as digestibility increased in order to maintain a constant intake of digestible DM; this implies a metabolic regulation to meet the metabolic needs. The transition point between physical and metabolic regulation for a 454-kg cow producing 16.8 kg of milk per day was 66.7% digestibility.

Montgomery and Baumgardt (1965a, 1965b) observed nearly constant intake by dairy heifers at 250 kcal of digestible energy (DE)/kg$^{0.75}$ for pelleted alfalfa-concentrate diets when digestibilities were greater than 55%. They attributed this transition from physical to metabolic regulation at a lower digestibility than observed by Conrad et al. (1964) to be caused by feed difference of pelleting, but the line for 250 kcal DE/kg$^{0.75}$ intercepts the curve of Conrad et al. (1964) where digestibility is about 55% (Waldo 1969). It is more likely that the transition point changes because of a lower metabolic requirement for a growing heifer than for a lactating cow rather than because of a direct feed effect.

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Location of the physical limitation for intake is implied to differ whether based on data from dairy cows fed mixed diets or on data from sheep or cattle fed primarily forage diets. Data of Conrad et al. (1964) imply a physical limitation at constant fecal excretion. Forages fed as pellets have increased intake and decreased digestibility compared to unground forages (Minson 1963). The decreased digestibility that accompanies this increased intake implies that the animals fed pelleted diets excreted more fecal dry matter than did those fed unground forages. Such a result is contradictory to the result of Conrad et al. (1964) and prevents the acceptance of the model of Conrad et al. (1964) as a general model. Pelleted forages produce less rumen fill but more fecal DM excretion than do unground forages, which implies a physical limitation in the rumen rather than a physical limitation in fecal output. These data seem to be in conflict and make the formulation of a general model more difficult, but there may be an animal factor that changes with lactation. Tyrrell and Haaland (1983) observed a shift in the fractional distribution of wet digesta from rumen to postruminal GI tract during lactation.

Montgomery and Baumgardt (1965b) introduced the concept of dietary energy density to translate weight to volume for a more appropriate relation to the physical limitation of space in the rumen. Bull et al. (1976) evaluated five mixed diets with bulk energy densities of 0.58, 0.63, 0.68, 0.84 and 1.17 Mcal of DE/liter fed to lactating cows; they showed that physical fill limited the intake of two diets with lower energy density, and metabolic regulation limited the intake of the three diets with higher energy density.

Substitution

Many practical diets are more economical if concentrates are fed with forages, so the substitution between forage and concentrate is important. Dulphy (1978) related substitution to intake of forage fed without concentrate for lactating cows. Proportional substitution as

$$Y = 0.404\ X - 0.418,$$

where Y = decrease in units of forage/increase in units of concentrate and X = intake of forage DM, when fed without concentrate, as a percentage of W with R^2=0.77 and n=32. This equation implies that the decrease in forage intake units as additional concentrate units are offered is greater for forages that have a high intake potential when fed alone. Conversely, this equation implies that forages having a higher intake potential will be consumed in larger amounts as concentrate is decreased. When forages of different intake potential are considered with concentrate, a response surface is generated. If concentrates are fed at 2% of W, then all forages will be consumed at about 0.5% of W, and the total diet will be consumed at about 2.5% of W. As the intake of concentrate is reduced, the intake of both forage and total diet must approach the inherent intake for that forage fed alone.

Relation of Intake to Digestibility and Cell Wall Concentration

Intake of forages is generally related to in vivo digestibility. Van Soest et al. (1978) found R^2=0.37 for this relationship in a set of 126 grasses and 61 legumes. At equal digestibility, legumes are generally consumed in greater amounts than are grasses (Demarquilly and Jarrige 1974, Van Soest 1965). Intake of temperate grasses and legumes is generally related to cell wall (CW) concentration. Mertens (1973) observed daily

$$\text{DMI } (g/kg^{0.75}) = 128.8 - 1.09CW \text{ (g/100 g of DM)},$$

with R^2=0.58 for 126 grasses and 61 legumes. Osbourn et al. (1974) found corrected daily organic matter intake (OMI)

$$\text{OMI } (g/kg^{0.75}) = 95 - 0.73CW \text{ (g/100 g of DM)},$$

with R^2=0.77 for 56 dried grass and legume forages fed to sheep. Probably, the reason for this higher correlation is that all data were collected at one location and were corrected to the intake of a standard forage. Daily

$$\text{DMI } (g/kg^{0.75}) = 153.6 - 1.10CW \text{ (g/100 g of DM)},$$

with R^2=0.93 (D.J. Thomson et al., unpublished data) for four alfalfa silages and four orchardgrass silages fed to Holstein steers or heifers. This slope compares very favorably with the slope observed by Mertens (1973).

Gastrointestinal Tract Fill

The GI tract fill resulting from different forages has major nutritional implications of: (1) physical volume limitation of fill in intake regulation, (2) physical mass contribution of GI fill to W or weight gain, and (3) possibility of increasing the energy requirements or decreasing energy utilization by animals. Presumably, greater intake of legumes than grasses at equal digestibility results from the smaller volume contribution of legumes to GI tract fill. Feeding standards generally do not consider the difference in GI tract fill, but the ARC (1980) has attempted to describe them. Weight of wet ingesta from the ad libitum feeding of legumes is much less than that from the ad libitum feeding of grasses (Joyce and Newth 1967, Rattray and Joyce 1974) which is inverse to their intakes. Slaughter-balance data (D.J. Thomson et al., unpublished data) indicate that the combined effect of different ratios of protein to fat deposition and different GI tract fill can cause a range in energy concentration of live-weight gain from 3.12 to 1.66 Mcal/kg. Dietary CW concentration may predict gut fill as it does intake. The

$$\text{GI tract fill (\% of W)} = 0.273CW + 4.9$$

with R^2=0.95 for two alfalfa and two orchardgrass silages (D.J. Thomson et al., unpublished data). The GI tract is very active tissue, metabolically (Webster 1981). Koong et al. (1982) observed higher fasted heat production in sheep fed larger rations and having larger organ sizes. Thomson and Cammell (1979) observed heavier reticulorumen tissue weights

relative to empty W for lambs fed chopped alfalfa than for those fed pelleted alfalfa. The total body energy retention relative to DM intake was less for the lambs fed chopped than for those fed pelleted alfalfa. The controversy of whether the metabolizable energy of legumes is (Rattray and Joyce 1974, Thomson and Cammell 1980, H.F. Tyrrell et al., unpublished data) or is not (Greenhalgh and Wainman 1980) used with greater efficiency for growth than the metabolizable energy of grasses is important enough to deserve further research. Larger GI fill of wet ingesta, and possibly gut tissue, for grasses than for legumes may be a mechanistic explanation for differences in energetic efficiency. Kellner's system of starch value (Nehring 1972) reduced the potential starch value by a product of percentage units of dietary crude fiber times reduction constants which increased from 0.29 to 0.58 as the percentage of dietary crude fiber increased from 4% to 16%. The net energy system used in France (Vermorel 1978) uses crude fiber as a reduction factor in the conversion of digestible energy to net energy. Presumably, the lower CW of legumes than grasses contributes to decreased GI tract fill, decreased GI tract tissue weights, and decreased heat production. Maybe CW would be an improvement over crude fiber for adjusting efficiency of utilization of DE as originally used by Kellner and as currently used in the French energy system. GI tract fill is certainly needed to translate W to animal product formed, and it may also be important to describe efficiency of converting forage energy to animal product.

Digestibility Depression Relative to Intake

Intake of forage-concentrate diets affects their digestibility so much that the potential increase in digestibility from concentrate addition is not realized as intake of concentrate is increased; in this case, the major factor causing a greater digestible intake is intake per se (Tyrrell and Moe 1975). Depression in digestibility due to increased intake also occurs when forages are fed alone. Osbourn et al. (1974) accounted for nearly all of the depression in DM digestibility with the depression in digestibility of CW fraction. Osbourn et al. (1981) found the depression of CW digestibility increased as forage particle size was reduced, as forage water-soluble carbohydrate concentration increased, and as forage buffering capacity decreased. The depression of digestibility at high intakes is larger for grasses than for legumes (Riewe and Lippke 1969) and even greater for the sorghums. The digestibility of legumes at high intakes is maintained better than the digestibility of grasses at high intakes, because legumes have a lower CW concentration than grasses per se, and digestibility is maintained indirectly by the generally lower sugar concentration and higher buffering capacity in legumes than in grasses.

Predictive Systems

Extensively developed systems for predicting intake are used in France (Jarrige 1978, Jarrige et al. 1979, Dulphy 1980). System reference for sheep is a fill unit for sheep (FUS) equivalent to 1 kg of a grass forage, which is consumed by a standard sheep at 75 g of DM/kg$^{0.75}$. System reference for cattle is an equivalent fill unit for cattle (FUC) at 122.6 g of DM/kg$^{0.75}$. For an unknown forage

$$FUC=122.6/(\text{intake of unknown as g of DM/kg}^{0.75}).$$

Intake capacity of an animal is fixed based on its physiological state. Intake capacities for animals in various physiological states are tabulated (Jarrige et al. 1979). Substitution (SUB) is described as a proportional decrease in forage units of intake/increase in concentrate units of intake. For growing and fattening cattle,

$$SUB=(1/FFV)(1-A\exp^{(B/(1.0-CON)}),$$

where FFV is the forage fill value as FUC, CON is the fraction of concentrate in the diet, and A and B are experimentally determined constants. For lactating cattle,

$$SUB=1-(FFV-0.975)^{0.33}.$$

Different fractions of concentrate give different substitution curves for growing and fattening cattle where SUB always approaches 1 as CON approaches 1, but a narrow range of data for lactating animals prevented such detail. Substitutions for both growing and fattening cattle and lactating cattle are curvilinear and give higher substitutions with forages that have lower FFV; that is, have higher intakes when fed alone. Both systems seem conceptually sound because they relate the intake of supplemented forages to the intake of forages fed alone. These systems being proposed in France consider both the animal and forage sources of variation.

Research Needs

Physical and chemical characteristics of forages that generally improve upon the prediction of intake from cell walls need to be identified.

The question of whether legumes, which have a higher intake potential than grasses, also cause a higher efficiency of transforming metabolizable energy into net energy, or animal product, than grasses needs to be resolved.

The prediction of gut fill from chemical and physical characteristics of forages and the inverse relation of gut fill from forages to intake of forages needs evaluation.

If the metabolizable energy of legumes is used by the ruminant with greater efficiency than that of grasses, the cause must be identified. If the cause is a difference in absorbed energy or protein, then supplementation will correct the problem. But if the cause is a greater intestinal fill, a greater intestinal tissue mass, and a greater oxygen requirement, then supplementation will only dilute the problem.

The intake response surface from the supplementation of forages that have different intake potentials with different levels of concentrate must be defined.

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Discussion

Jorgensen: The assay for cell walls has not yet been approved in the United States. Do you think Dr. Mertens (Georgia) will get it approved?

Waldo: Yes, Dr. Mertens has a good chance of success.

Helyar: A point of clarification. What are you buffering in the rumen?

Waldo: You are buffering the volatile fatty acids produced in the rumen. In silage fermentation, a low buffering capacity is desirable because it requires less acid to reach a stable pH, whereas in the rumen a high buffering capacity is desirable because greater digestion and acid production occur.

Reid: A comment on the ratio of the foregut and the rest of the gut. Work at Ruakura and elsewhere shows that the rumen is reduced in size during pregnancy and takes time to return to normal.

Waldo: I agree.

Ulyatt: There is a difference in efficiency of utilization of metabolizable energy between legume and grasses. What causes these differences?

Waldo: Two potential differences are either the carbohydrates fermented and their absorbed end products or the essential amino acids available for absorption in the small intestine. Our group is adding a possible third difference contributing to the legume/grass difference--gastrointestinal tract fill. There is more gastrointestinal tract fill and gastrointestinal tract lean tissue in animals fed orchardgrass than when fed alfalfa. This gastrointestinal tract lean tissue is very active metabolically and may cause slightly larger oxygen consumption in grass-fed than legume-fed animals.

Breeding Bloat-Safe Cultivars of Bloat-Causing Legumes

M.D. Rumbaugh

Abstract

Legume pasture bloat is induced by a complex of animal, plant, microbial, and environmental factors. Plant species have been characterized as being bloat-safe or bloat-causing on the basis of grazing experience, but there seems not to be a single well-defined or easily identifiable biochemical or structural difference between plant groups so characterized. Therefore, each legume species should be examined critically, the bloat-causing entity determined, and a screening technique developed prior to initiation of a breeding program. Divergent selection with both bloat-safe and bloat-causing species must be coupled with animal response trials to fully explore all plant factors involved in bloat. Index selection, mutation breeding, wide crosses combined with embryo rescue, and genetic engineering procedures may all be applicable.

Bloat is a disease of ruminants characterized by an accumulation of gas within the reticulo-rumen in sufficient quantity that usual pressures are exceeded and distention results. Normal fermentation processes within the reticulo-rumen generate carbon dioxide and methane. Bloat only results when the animal cannot decrease rumen pressure by eructation. This release of gas may fail when the gas is trapped within the rumen ingesta in the form of a stable foam (Boda et al. 1956). Foaming is considered by many investigators to be the most important factor influencing expulsion of the gas and, therefore, the incidence of bloat (Cole and Boda 1960).

Bloat is expensive. Approximately 0.06% of the beef and 0.40% of the dairy cattle on farms and ranches in the United States have been estimated to die from bloat (U.S. Department of Agriculture 1965). Daily bloat rates in experimental environments where cattle grazed alfalfa (*Medicago sativa* L.) were 7.3% for control animals and 1.9% for animals receiving a poloxalene preventative (Acord et al. 1969). Based on experience, the mortality of cattle grazing alfalfa is expected to be somewhat below 1.0% (Hayes et al. 1980). Total annual losses in the United States through bloat-induced mortality and morbidity were estimated to be more than 100 million dollars in 1965 (U.S. Department of Agriculture 1965). Adjusted to 1982 values, this loss would be 311 million dollars. Such estimates do not include: (1) reduced animal productivity because bloat-inducing legumes are partially or entirely avoided in farm and ranch operations, (2) cost of treatment of animals, and (3) extra labor incident to the disease or to prevention of the disease (Jacobson 1967). These losses are probably far greater than those due to mortality and morbidity. Legumes can provide a higher level of forage production through the summer months in temperate subhumid climatic zones than any perennial grasses under any system of management (Jackobs 1967). However, the danger of bloat in ruminants has been a great deterrent to pasture improvement based on our most productive legume species.

It is less commonly recognized that an identical problem and possibly an even larger indirect economic loss occurs on semiarid rangelands. Alfalfa and other bloat-causing legume species have been used in range reseedings with dramatic gains in both the quantity and quality of forage (Rumbaugh et al. 1982, Kartchner et al. 1983). Benefits to both livestock and wildlife have resulted (Rumbaugh 1983). However, most ranchers hesitate to use these plant species since they perceive bloat to be a potential source of stock loss (Johnston 1952). The development of appropriate selection techniques and criteria to allow the breeding of adapted, productive, bloat-safe legume cultivars would do much to restore or increase the profitability of livestock farming and energy-efficient agriculture.

There have been at least eight extensive reviews of bloat: (1) Cole et al. 1956, (2) Cole and Boda 1960, (3) A.E. Staley Manufacturing Co. 1967, (4) Leng and McWilliam 1973, (5) Clarke and Reid 1974, (6) Howarth 1975, (7) Walgenbach and Marten 1980, and (8) Goplen et al. 1983. Although there is a general agreement that bloat is caused by the formation of intraruminal foam that inhibits the eructation of gases produced by microbial fermentation, there is not yet a consensus as to the basic precursor of the foam or how to select bloat-safe genotypes within plant species which are regarded as causing bloat. Certain legumes, for example, sainfoin (*Onobrychis viciifolia* Scop.), birdsfoot trefoil (*Lotus corniculatus* L.), and cicer milkvetch (*Astragalus cicer* L.), are regarded as low-risk or bloat-safe legumes, whereas others such as alfalfa, white clover (*Trifolium repens* L.), and red clover (*T. pratense* L.) are considered to be high-risk or bloat-causing species when grazed. Yet consideration of the biochemical differences between these two categories of species has not yet led to welldefined breeding procedures which can be applied in plant screening and selection programs. The current state-of-the-art was outlined recently by Goplen et al. (1983).

Animal Factors

Livestock producers and bloat investigators have observed a wide variation in animal susceptibility to bloat (Clarke and Reid 1974). Some animals seldom or never bloat, whereas others bloat easily and severely. Bloat susceptibility appears to be partly heritable, and it may be possible to select cattle that are more resistant than present breeds (Reid et al. 1972, Cockrem and McIntosh 1981). Although many variables probably influence animal susceptibility, lactation, age, calving date, and butterfat production were shown to have little association with bloat (Cockrem and McIntosh 1976). Salivation, degree of hunger, rate of eating, and degree of selective eating may often be of consequence in the occurrence or prevention of bloat (Walgenbach and Marten 1980).

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Plant Factors

Pectins

Pectins do not function as primary foaming agents, but they may increase the viscosity of rumen fluid and act as foam stabilizers (Wright 1961). Increased viscosity would decrease the drainage of liquid in the foam lamellae and thereby increase foam persistence (Jones et al. 1978). Rumbaugh (1972) found a significant correlation (r=0.86) between pectin methyl esterase activity and the in vitro stable foam volume of freshly harvested alfalfa. However, no legume species has been selected for a low pectin content, and the impact of doing so on plant development, productivity, and bloat risk is unknown at this time.

Lipids and Lipoproteins

Negative associations have been detected between concentrations of phospholipids from plant chloroplasts and ruminant bloat severity (Stifel et al. 1968a). The surface tension of rumen fluid, and hence the volume of foam, is reduced by lipids.

Rommann et al. (1971) found a positive association between the amount of lipoproteins and the in vitro foaming capacity of six clones of alfalfa. They believed that lipoproteins might act as surfactants which could, in part, be responsible for the formation of stable foam during ruminant bloat. Howarth et al. (1977a) showed that alfalfa lipoproteins do not have any unique role in the development of frothy rumen contents but act in the same way as other soluble proteins. Much of the lipid is reversibly bound to proteins and is polar lipid. Such polar leaf lipids have antifoaming properties (Clarke and Reid 1974) and hence would not cause bloat. However, true lipoproteins may produce more viscous foams than other soluble proteins.

A threefold variation in epicuticular wax content among 10 populations of white clover and a fivefold variation among 10 populations of red clover were measured by Moseley (1983). There were no major qualitative differences between the waxes of the two species or among the populations. Ingestion of epicuticular waxes by animals could provide a source of naturally occurring antifoaming agents.

Saponins

Opinion as to the role of saponins in the etiology of bloat has changed since Cole and Boda's 1960 review. Based on evidence obtained prior to that time they stated, "No doubt saponins play a role in the foaming of ruminal ingesta and, thus, in the production of bloat." By 1976 saponins had been relegated to a secondary role either as foaming agents or as the cause of toxic inhibition of reticulo-rumen activity (Cheeke 1976). The critical test was conducted at Kamloops, British Columbia, where rumen-fistulated animals were fed fresh herbage from near-isogenic strains of high- and low-saponin alfalfas (Goplen et al. 1979, Majak et al. 1980). There were no significant differences between the alfalfa strains in the occurrence of bloat or of frothy rumen contents. Saponin concentrations in rumen fluid were generally below detectable levels and below the estimated level of toxicity to the animals.

Soluble Protein

Mangan (1959) suggested that the foaming agent was soluble cytoplasmic protein. McArthur and Miltimore (1966) and Stifel et al. (1968b) erroneously identified the responsible component as 18 S or fraction I protein. Further investigations in New Zealand (Jones and Lyttleton 1972) and Canada (Howarth et al. 1973a, 1977a, 1977b) implicated both fraction I and fraction II as factors responsible for bloat. The Saskatchewan laboratory developed a rapid and reliable test for soluble proteins based on the colorimetric biuret method (Howarth et al. 1973b) and immediately initiated a screening program to develop contrasting alfalfa populations of low- and high-soluble protein contents (Goplen et al. 1983). As indicated by moderately low heritability estimates of h^2=0.23 to 0.31 (Gutek et al. 1976), genetic changes were limited. After two cycles of divergent selection, one population contained 11.07% soluble protein and the other 13.76%. The slow rate of progress, coupled with an estimate that a 50% minimum reduction in soluble protein concentration would be required to breed a bloat-safe alfalfa cultivar (Howarth et al. 1977a), reinforced a decision to suspend this research in 1980 (Goplen et al. 1983). Concurrently, preliminary information on cell-wall rupture and initial rate of digestion techniques developed in the same laboratory appeared to be promising selection criteria.

Tannins

Based on laboratory foam volume test procedures, Kendall (1966) suggested that tannins in bloat-safe legume species were responsible for preventing pasture bloat. This was confirmed by other laboratories (Jones and Lyttleton 1971, Gutek et al. 1974). Water-soluble condensed tannins or flavolans prevent bloat by precipitation of proteins (Sarkar et al. 1976). The vanillin-HCl test described by Burns (1963) was modified to ensure detection of condensed tannins (Sarkar and Howarth 1976). Alfalfa leaf tissue is known to contain approximately 1.6% phenols (Martensson 1979) but not the condensed tannins required to reduce bloat potential. The latter are present in the seedcoats of alfalfa but not in the foliage (Goplen et al. 1980). Surveys in three laboratories have failed to discover plants of any *Medicago* species with foliar condensed tannins (Rumbaugh 1979, Goplen et al. 1980, Marshall et al. 1981). The concentration of tannin in leaves of legume species in which these compounds are usually present has been found to be a highly heritable trait, with the presence of tannin dominant over its absence (Marshall et al. 1981, Dalrymple 1982). This has encouraged mutation breeding as an approach to developing a condensed tannin-bearing alfalfa. This conceptually simple task may be prolonged because 4.65×10^5 cell progenies must be examined to be 99% certain of detecting a single dominant mutation in mutagen-treated populations (Brock 1971).

Cell Wall Structure

Cell walls of three bloat-causing legumes, alfalfa and red and white clover, are thinner and disintegrate faster during cellulase digestion than those of two non-bloat-causing legumes, sainfoin and cicer milkvetch. Two laboratories have developed in vitro procedures to screen plants for resistance to cell disruption by enzymes (Sant and Wilson 1982, Goplen et al. 1983). At Aberystwyth, Wales, initial populations of 100 plants of each of two red clover cultivars, 'Sabtoron' (diploid) and 'Norseman' (tetraploid), were subjected to a pepsin-cellulase solubility time test. From each population, the five genotypes with the slowest and the five with the fastest cell wall disintegration were chosen as parents in a divergent selection program. The genetic gain and realized heritability for slower disintegration time were greater in the diploid (h^2=1.13) than in the tetraploid (h^2=0.10). Similar tests are being used in Canada to evaluate alfalfa seedlings. Animal response data for divergently selected plant populations are not yet available.

Microbial Factors

Gases from microbial digestion of forage remain dispersed throughout the rumen ingesta in pasture bloat. Reduction or alteration of the microbial population in the rumen by administration of antibiotics has been studied extensively as a possible bloat prevention measure (Cole and Boda 1960). Recently, the interaction of the bacterial and plant components of bloat were investigated. Bacterial penetration of legume leaf tissue cell walls proceeded by means of a general disintegration rather than by the specific pit formation earlier observed with grasses (Cheng et al. 1980). The time required for bacterial penetration through the leaf tissue was greater in bloat-safe than in bloat-causing legume species (Howarth et al. 1978). Also, the amount of foam produced during in vitro digestion of chewed leaves was greater with bloat-causing than with bloat-safe species (Fay et al. 1980). The variation inherent in the in vitro digestion procedure was high. Goplen et al. (1983) were of the opinion that the variation would need to be reduced before the procedure could be used as a bioassay to differentiate between bloat-safe and bloat-causing selections in a plant-breeding program.

Environmental Factors

Environment influences the chemical composition of living plants and, presumably, their bloat potential (Walgenbach and Marten 1980, 1981a, 1981b; Walgenbach et al. 1981). Livestock producers are convinced that bloat is most likely to occur under certain environmental conditions, but until recently none of these factors had been properly investigated by scientists. Measurements of the soluble protein concentration of alfalfa grown in Minnesota showed that bloat risk may be increased by fertilization with very high levels of N, use of cultivars with high N-fixation capacity, and growing plants when air temperatures are at or near 26°/18°C. Bloat potential might decrease during long periods of cloudy weather. Other elements considered to be important by farmers and ranchers such as recency of precipitation or irrigation have yet to be properly investigated.

Selection Criteria

In Vitro Foam Volume and Strength

The initial report by Mangan (1959) of a similarity in characteristics of a foam generated in vitro with an extract of red clover leaves and bovine rumen liquor from bloating animals stimulated investigation of laboratory foam tests as possible screening procedures for the selection of legume plants with low bloat potential. Mangan's apparatus (Mangan 1958) enabled measurement of the expansion, dynamic stability, and strength of foams. Air at a constant pressure and flow rate was passed through a liquid to generate a foam, and foam strength was measured by the rate of fall of a perforated brass weight through the foam. Pressey et al. (1963) reported a significant positive correlation (r=0.56) between in vitro foam strength and the incidence of bloat in cattle grazing alfalfa plots. Investigations with 'Caliverde' alfalfa (Glover and Stanford 1963) showed that foam strength was affected by dilution of the plant juices, pH, tissue preservation methods, and age of the plant material. Because of the high variability accompanying individual determinations, they did not detect significant differences among alfalfa clones.

A simpler technique suitable for assaying a larger number of samples was developed by Kendall (1964). Although he was able to show differences in the foam volumes of six legume species, and, in one test, among three alfalfa cultivars, variability between samples within ten red clover clones was very high and there were no significant differences among the clones. Modification of the procedures by use of a pH 5.6 buffer chilled to 5°C resulted in less variability, and detection of clonal differences was possible (Kendall and Taylor 1965). A close relationship between foam volume and the known bloat potential of 27 legume species was demonstrated with these techniques (Cooper et al. 1966).

Rumbaugh (1968) further modified the foam-volume procedure to allow large numbers of plants to be evaluated in relatively short intervals. Precision of the test was sufficient to detect significant differences among 100 clones of 'Vernal' alfalfa with a coefficient of variation of 7%. Analysis of a 12-clone diallel cross provided a heritability estimate of h^2=0.73 for stable foam volume of alfalfa (Rumbaugh 1969). This high heritability indicated that breeding a low-foaming cultivar should be possible. Canadian scientists, however, considered the foam-volume theory of bloat invalid since their data resulted in only nonsignificant correlations of foam volume with soluble protein (Goplen and Howarth 1977) and with bloat incidence (Goplen et al. 1983). The magnitudes of all correlations in their studies were low. Over a 3-year period, the coefficient of determination relating total soluble protein concentration and bloat incidence was 0.11, whereas that for in vitro stable foam volume and bloat incidence was 0.05 (Howarth et al. 1977a).

In Situ Nylon Bag Initial Rate of Digestion (IRD)

Grazing experience has shown that cicer milkvetch is a bloat-safe legume (Johnston et al. 1971, Seamands et al. 1972), yet it does not contain condensed tannins (Sarkar et al. 1976). Another bloat-safe legume species, birdsfoot trefoil, contains only small amounts of condensed tannins during the prebud stage of growth yet can be grazed without bloat risk (Gutek et al. 1974). The amounts of soluble protein nitrogen and chlorophyll were substantially lower in the rumen fluid of sheep fed bloat-safe legumes than in those fed bloat-causing species (Howarth et al. 1979). Investigation proved that leaf mesophyll cells of bloat-safe legumes were more resistant to mechanical rupture than those of bloat-causing species (Howarth et al. 1978). Lees et al. (1981a, 1981b) confirmed this and differentiated cell wall rupture and tissue damage into two separate, although related, entities. Birdsfoot trefoil had strong cell walls alone, whereas sainfoin and cicer milkvetch had moderately strong cell walls combined with a high degree of tissue strength. Alfalfa and white clover, both of which cause bloat, had weak cell walls with low tissue strength, while red clover, another bloat-inciting species, had moderately strong cell walls and low tissue strength. The cell rupture theory of legume pasture bloat proposes that the rate of release of soluble protein is a determinant factor in bloat development. Slow digestion rates may explain why species such as arrowleaf clover (Trifolium vesiculosum Savi.), which are high in soluble protein and susceptible to rupture by sonication but which do not contain condensed tannins or have thick cell walls, are bloat-safe (Howarth et al. 1983).

This selection technique is now the primary screening method being used in Saskatoon, Saskatchewan, to develop a bloat-safe alfalfa cultivar. Since it measures relative digestion rates in situ and combines the effects of mechanical disruption and microbial digestion, it is regarded as the most reliable selection test to date. It has been estimated that a 20 to 30 percent reduction in the IRD (initial rate of digestion) of alfalfa will be required to produce a bloat-safe cultivar. Obviously the procedure is an expensive screening mechanism, and information as to heritability and genetic progress has not yet been reported.

Future Research

While the complex nature of the etiology of bloat cannot be denied, there are some informational and procedural needs that can be investigated by fairly simple research. The only critical evaluation of a plant factor as a putative cause of bloat has been the evaluation of high- and low-saponin alfalfas in animal trials conducted at Kamloops, British Columbia. Plant populations should be divergently selected by the stable foam volume, initial rate of digestion, and other proposed screening procedures until the subpopulations are markedly differentiated. Animal responses to the high and low subpopulations are essential for validation or rejection of theory. Too often we have initiated and abandoned plant-selection programs as new theories of the cause of bloat have been advanced in rapid succession.

One approach to evaluating the significance of plant factors as causes of bloat which has not been tried is the divergent selection of known bloat-safe species. If cicer milkvetch is bloat safe because of its thick cell walls, it should be possible to breed a bloat-causing strain by reselection for thin cell walls. Bloat incidence and severity in grazing trials would provide the final definition of the component in bloat etiology.

There is considerable potential for breeding red and white clovers and possibly other legumes with higher levels of epicuticular waxes. Further research is required to establish the extent to which epicuticular waxes may reduce the stability of rumen foams.

If a single plant factor cannot appropriately be designated as the most important precursor of bloat, index selection must be considered. Simultaneous measurement of soluble protein may be combined with stable foam volume, initial rate of digestion, and other data into an approximate index even if the genetic relationships among the traits have not been estimated precisely.

Mutation breeding to develop an alfalfa with condensed tannins in the forage has not been successful. However, the objective has not been sought through a large-scale program, and these efforts should continue. Recently developed genetic engineering techniques may have value in transferring the gene or genes from condensed-tannin-producing species into species which do not have condensed tannins. In some cases, wide crosses of distantly related bloat-causing and bloat-safe species combined with embryo rescue techniques may be all that is required.

An indirect method of solving the problem would be to develop complementary cultivars of bloat-safe and bloat-causing legumes and to use them in mixed stands. Intake of a small quantity of a bloat-safe legume may eliminate the risk of bloat when ruminants graze a more productive but bloat-causing species.

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Discussion

Syers: Dr. Max Turner at Massey University claims to have found an association between the ratio of K/Na in mixed pasture and the incidence of bloat. A wide K/Na ratio was associated with a high incidence of bloat, and a narrow K/Na ratio was associated with a low incidence of bloat. Have you any evidence of such a relationship?

Rumbaugh: We have no understanding of this, but it would be interesting to check it out.

Barry: If you offer bloat-inducing and non-bloat-inducing species together to the animal, what is the result?

Rumbaugh: We have done this with stable-foam-volume tests with alfalfa and sainfoin; the result was less than half that expected. The cultivars would need to be complementary in habit to avoid grazing selection in the field.

Reid: We ran a farm experiment with animals grazing sainfoin and lucerne for varying times. There was some beneficial effect to allowing the animals to graze the sainfoin.

Knight: Is the genetic trait of the animal involved in bloat? If so, is it possible to select animals for bloat resistance?

Rumbaugh: This is being done in New Zealand.

Reid: We are not sufficiently far ahead to prove this, but we feel that the prospects are better with the plant.

Easton: This should help our understanding of what is happening in plants, because salivary proteins are included in bloat.

Reid: Salivary proteins are correlated with the incidence of bloat but may not be involved.

Rumball: Ulyatt and Rumbaugh have been considering different factors in bloating, but tannins are a common factor.

Rumbaugh: Yes, at certain levels.

Runge: How many more plants are you going to test?

Rumbaugh: We are routinely testing everything.

Barry: In birdsfoot trefoil, the concentration of tannin varies from 3%-4%. Do you know at what level they lose the ability to prevent bloat?

Rumbaugh: The test I have used gives a + and -, but I have not measured the actual level. The general feeling is that birdsfoot trefoil is safe.

Toxic Factors in Tropical Legumes

Dennis J. Minson and Mervyn P. Hegarty[1]

Abstract

In the review, Leucaena leucocephala (leucaena) is used as a model to illustrate the different factors that determine legume toxicity; other toxic legumes are briefly described according to the mechanisms associated with their toxicity. The level of toxin or toxin precursor can be up to 10% of the dry matter, but the potential effects may be modified by (1) avoidance by the animal, (2) conversion by plant enzymes into compounds which may be of lower or higher toxicity than the original toxin or toxin precursor, (3) conversion by rumen microflora, and (4) transformation of the toxin in the liver.

It is suggested that legume toxicity may be reduced by selecting and breeding plants with lower levels of toxin or toxin precursor, by inoculating the rumen with appropriate bacteria where it is shown that these are required and are available, or by management strategies that reduce the proportion of legume in the diet.

Introduction

Legumes are generally excellent sources of energy and protein for grazing ruminants, but sometimes the presence of toxic factors in the feed reduces production below the expected level. Higher plants contain a wide range of substances which depress animal production: alkaloids, amino acids, cyanogenic glycosides, goitrogens, organic acids such as oxalic and fluoroacetic acid, oestrogenic isoflavones, and other polyphenols and saponins (Butler and Bailey 1973). Although many of these substances occur in tropical legumes, they often fail to have the expected detrimental effect on animal production.

In his comprehensive handbook on tropical forage legumes, Skerman (1977) lists twenty-four genera of pasture legumes and twenty-six of browse legumes. Only a limited number of species within four genera in each of these two categories have been shown to be toxic (table 1). Few of these species cause acute toxicity in ruminants, and their effects are usually limited to reduce production of meat, milk, or wool. There is a paucity of information, and in only a few legumes have the toxins been identified and their mechanisms of action determined. Even less is known about the metabolism of these compounds in the rumen and after absorption into the animal, although extensive information is available on these aspects of the toxicity for temperate forage legumes (e.g., cyanoglucosides in Trifolium sp., oestrogenic isoflavones in T. subterreaneum, and pyrrolizidine alkaloids in Crotalaria sp.). The exception is Leucaena leucocephala (leucaena), a tropical browse legume. In this paper, leucaena will be used as a model to illustrate the different factors that may determine whether or not a forage legume is toxic. Other tropical legumes will be classified according to the mechanisms associated with their toxicity.

Plant Factors That Influence Potential Toxicity

Concentration of Toxins or Their Precursors

The concentrations of toxins vary widely among legumes and in some cases can be remarkably high: 10% mimosine in the dry matter of leucaena leaves (Hegarty et al. 1964) and 2%-4% indospicine in the seed and 0.4% in the leaves of Indigofera spicata (Hegarty and Pound 1970). Both these toxins occur in the leaves and seeds, and animals eating plants with immature seed pods may ingest large quantities of the toxin. Typical analyses of the Peru cultivar of leucaena gave the following mimosine contents on a dry weight basis: tips, 6.8%; first leaf, 3.2%; fifth leaf, 1.4%; and tenth leaf, 0.9% (Hegarty and Court 1971).

I. spicata and other Indigofera species also contain 3-nitropropanoic acid that is toxic to non-ruminants and has been suspected of being toxic to ruminants in high concentrations (Britten et al. 1963). However, this compound occurs only in the leaves. Nitrogenous toxins (e.g., cyanoglucosides, amino acids, and alkaloids) are commonly present in highest concentration in meristematic tissues, and therefore management practices that continually provide animals with a diet of young regrowth should be avoided.

Environmental conditions and fertiliser practice can cause marked changes in the concentrations of toxin in the leaves of legumes. Nitrogen fertilisation usually causes increases in the concentrations of the nitrogenous toxins such as amino acids, cyanoglucosides, and some alkaloids; while moisture stress has increased the mimosine content of leucaena (R.A. Bray and Jan Hoekstra, unpublished data). Some Acacia species contain other compounds that adversely affect animal production. Acacia aneura (mulga) contains tannins (up to 7% DM of tannic acid equivalent) and oxalic acid (1% soluble oxalate) that may depress the availability of sulphur and calcium in the diet (Gartner and Hurwood 1976). Another Acacia species, A. salicina, often used to feed sheep in central Queensland in times of drought, has sometimes caused acute toxicity, probably because of its extremely high tannin content (14%) (McCosker and Hunt 1966). Acacia georginae leaves contain small amounts of the highly toxic fluoroacetic acid, the young leaves having higher concentrations than the older ones (McEwan 1978).

Conversion by Plant Enzymes

Mimosine in leucaena is a potent depilatory agent in both ruminants and non-ruminants (Yoshida 1944, Hegarty et al. 1964). However, once eaten, enzymes present in the leaves and green pods rapidly transform the mimosine into 3-hydroxy-4(1H)-pyridone (DHP) (Smith and Fowden 1966, Lowry et al. 1983).

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Table 1 - Deleterious substances in some tropical legumes

Genus	Substance	Effects on animals
Indigofera	Indospicine	Hepatotoxic Teratogenic
Leucaena	Mimosine 3-Hydroxy-4(IH)-Pyridone	Depilatory Goitrogenic
Acacia	Cyanoglucosides Tannins Fluoroacetic acid	Death Acute Toxicity Death
Crotalaria	Pyrrolizidine alkaloids	Hepatotoxic
Tephrosia	Unidentified	Cardiotoxic Hepatotoxic

During ingestion and mastication by goats, about 30% of the mimosine in fresh leucaena leaves was converted into DHP before it entered the rumen (Lowry et al. 1983). Plant enzymes are generally inactivated by drying, and when dried leucaena is fed to ruminants, other sources of enzyme are required for conversion of mimosine into DHP.

DHP is non-depilatory but is a potent goitrogen with low acute toxicity (Hegarty et al. 1979). Thus the pharmacological properties of leucaena have been substantially altered by conversion of mimosine into DHP. The symptoms of DHP toxicity from high intakes of leucaena in ruminants in Australia include depressed appetite, weight loss, enlarged thyroid glands, and low serum thyroxine concentrations (Jones 1979).

In some tropical legumes the toxins occur in combined form. Examples are the cyanoglucosides in Acacia species and the glucoside esters of 3-nitropropanoic acid in some Indigofera species. The enzyme that hydrolyses these compounds, β-glucosidase, is widely distributed in plants and microbes. Where the ingestion of cyanogenic plant material produces acute cyanide toxicity shortly after ingestion, it is likely that both the glucoside and the enzyme come from the plant. In ruminants, hydrolysis by plant enzymes will continue without inhibition since the rumen will be at a pH 6-7 and further hydrolysis will be caused by the rumen bacteria (for review, see Conn 1978). Acute cyanide toxicity in ruminants has been reported in India from Acacia leucophloea (Prasad et al. 1977). Cyanoglucosides have been detected in a number of Australian Acacia species (Everist 1981). However, the four Australian Acacia species tested so far (Secor et al. 1976) do not contain β-glucosidase, and the risk of acute poisoning by these species is greatly diminished if the hydrolytic enzymes are lacking. No information is available on the contribution of the plant enzyme to the ruminal hydrolysis of the nitropropionyl glucose esters in Indigofera species (Majak and Clark 1980).

Animal Factors That Can Influence Toxicity

Palatability

The quantity of toxin consumed by animals depends on both the concentration of the toxin in the legume and the quantity eaten. Some legumes have high levels of toxin and are potentially dangerous but rarely cause problems because they are not usually eaten by stock (Crotalaria spp). Other legumes are potentially toxic but do not cause adverse effects in the animal because the proportion of legume in the diet is low or there is a system for detoxification.

Conversion by Rumen Microbes

Rumen microbes are another source of enzymes for transforming toxic or potentially toxic plant compounds. This metabolism of ingested compounds by rumen microbes can be considered as a first line of defence, a subject reviewed by James et al. (1975) and Allison (1978). In most situations the transformation results in detoxification of the plant toxin, but it is also possible for the transformation to enhance the toxicity or to change the nature of the toxicity. For these changes to occur, the appropriate microorganism must be initially present or produced in the rumen and sufficient time allowed for sufficient numbers to develop.

The transformation of mimosine to DHP by plant enzymes has been discussed previously. Once the leucaena has reached the rumen, any remaining mimosine is usually transformed to DHP by rumen microorganisms (Hegarty et al. 1964, Shiroma and Akashi 1976).

Leucaena toxicity caused by mimosine/DHP has been reported in Australia and several countries in Africa and Asia. However, in Hawaii, cattle and goats grazing leucaena of similar mimosine concentrations to those found in Australia showed no symptoms of leucaena toxicity (Jones 1981). This

absence of toxicity was associated with a low level of DHP in the urine, indicating that DHP had been metabolised. This metabolism appears to take place in the rumen and can be promoted by inoculating with rumen microbes collected from animals with the ability to metabolise DHP (Jones and Lowry 1984).

Some other potentially toxic compounds in tropical legumes (e.g., 3-nitropropanoic acid in Indigofera species) are destroyed in the rumen and cause problems only when the intake of the toxin exceeds the rate of detoxification (Majak and Clark 1980). Indigofera species also contain the hepatotoxin indospicine, but no information is available on the extent to which it is metabolised in ruminants, although in the Northern Territory Indigofera linnaei is known to be toxic to horses but not to cattle. Hydrogen cyanide from acacias is transformed into the goitrogen thiocyanate in the rumen and in the liver.

Transformations of Toxins in the Body

Once the toxic substances have been absorbed from the digestive tract, their toxicity can be altered in a number of ways within the body. Substances containing hydroxyl groups are usually conjugated as the glucuronides or sulphate esters principally in the liver and are then excreted in the urine. Conjugation invariably causes a substantial reduction in the activity of the toxin, with the inhibitory activity of DHP towards the thyroidal enzymes being reduced by a factor of more than 100 on conjugation (Christie et al. 1979). There are differences between species of animal in their capacity to conjugate toxins with cattle conjugating a higher proportion of DHP in serum than sheep (Hegarty et al. 1964, 1979). This conjugation enables cattle to absorb large quantities of DHP without adverse effects, although free DHP is a potent goitrogen (Hegarty et al. 1979).

Some Crotalaria species contain pyrrolizidine alkaloids which are converted by mixed function oxidases or cytochrome P450 system of the liver into potent liver toxins (Mattocks 1978). Modification of liver enzymes is not a practical way of protecting animals against these toxins (Culvenor 1978).

Future Work

The need for legumes in tropical pastures will lead to the introduction of new legume species. Past experience has shown that tropical legumes can be toxic, and it would be wise to screen all new legumes of toxicity. This would involve studies with non-ruminants and ruminants, together with appropriate chemical analysis.

Ruminants grazing in the tropics can be exposed to a number of potentially toxic legumes, and it is desirable to have ways for either eliminating the toxins from these plants or protecting the animals against the toxins. One solution is to develop, by selection or breeding, toxin-free plants or plants low in toxins. This has been partially successful with leucaena (R.A. Bray, E.M. Hutton and W.M. Beattie, unpublished data) but is expensive, time-consuming, and probably only warranted if other methods of overcoming the problem are not available. The recent and unexpected discovery of the need to inoculate that rumen of Australian animals before they can completely detoxify leucaena (Jones and Lowry 1984) offers an interesting biological solution to legume toxicity. This result with leucaena is probably the first documented example of any advantage being obtained by inoculation of the rumen, although is has been recognised for over half a century that legume seed often needs to be inoculated with the appropriate Rhizobium to be fully effective in fixing nitrogen.

This observation raises a simple question of whether there are other pasture legumes that are toxic in Australia or other parts of the world due to the absence of the appropriate detoxifying microorganism. Is it possible that the infertility problems in Australia associated with oestrogenic compounds in clovers may be caused by the lack of the appropriate rumen bacteria and that these might exist in some other part of the world? Jones and Lowry (1984) have recently suggested that "in the light of these results with leucaena, the possibility should be explored that other introduced pasture plants that are toxic to ruminants in a particular country may not be toxic in their country of origin." Those toxic substances which could yield large quantities of energy to bacteria on degradation are more likely candidates for bacterial breakdown than complex substances occurring in small quantities.

There is a need to determine whether there is a difference in the world distribution of rumen bacteria capable of metabolising the toxins in legumes. This would require the establishment of an international research program which would determine for a number of important legumes whether the detoxification processes in ruminants are the same in all countries. If it is shown that differences in metabolism and detoxification occur between sites, then the possibility that rumen bacteria are involved should be checked by rumen inoculation. Where only partial detoxification is achieved by the rumen bacteria, modern recombinant DNA techniques might be used to develop fully effective bacteria.

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Discussion

Collins: You consider that inadequate adjustment periods have been used for species with potential problems. In some cases, it may be impractical to take the risk of grazing.

Minson: The problem is not serious when the same species is grazed all the time. The problem occurs during the changeover from one feed to another; an adjustment phase would largely overcome this problem.

Marten: Has anyone documented an association between toxicity and palatability in leucaena?

Minson: No association between toxicity and palatability has been documented. However, Dr. Ray Jones found that as soon as the rumen microbes capable of detoxifying DHP were introduced, intake increased and had doubled after a few days.

Marten: A similar effect occurs for alkaloids. The threshold for intake effects (0.2%) is lower than for palatability (0.6%).

Bray: Leucaena is a very palatable species even though it is high in mimosine.

Bray: You suggested breeding for low mimosine or selecting for microbes to control toxins. Perhaps the main way of avoiding toxicity problems is by management of animals and pastures.

Minson: Management is important. Although the presence of the detoxifying microbe may increase intake, there has rarely been problems in 20 years' use at Samford Research Centre.

Lancashire: Are Australian farmers accepting leucaena or are they put off by occasional leucaena poisoning?

Bray: Leucaena is not widely accepted for grazing, not because of the toxin but because of establishment difficulties. The management package is not well developed.

Minson: Leucaena is more widespread than generally thought. It has been accepted in overseas countries (e.g., Indonesia) where cheap labour is available for planting.

Collins: What about the decline in mimosine with leaf age?

Minson: It is probably a straight dilution.

Bray: There is a need for labelled mimosine to study the problem of different concentrations of mimosine.

Minson: Mimosine may be useful. It is claimed that leucaena has few pests and this may be due to the mimosine.

Nutritional Effects Attributable to Condensed Tannins, Cyanogenic Glycosides and Oestrogenic Compounds in New Zealand Forages

T.N. Barry and C.S.W. Reid[1]

Abstract

Condensed tannins (CT) confer both beneficial and detrimental effects, depending upon tannin molecular weight (MW) and reactivity with proteins. High concentrations (6%-10% DM) of low MW (7,000) reactive tannins in Lotus spp. depress voluntary intake and rumen carbohydrate (CHO) digestion but are highly efficient at reducing ruminal plant protein degradation and increasing amino acid supply to the animal. High MW (23,000) tannins in sainfoin (6% DM) are not quite so efficient at increasing amino acid supply but do not depress rumen CHO digestion. Legumes containing substantial concentrations of CT in leaf and stem tissue (i.e., Lotus spp. and sainfoin) do not cause bloat, due to precipitation of soluble plant proteins in the rumen; however, legumes containing CT in flower petals only (i.e., white and red clover) do cause bloat due to physical separation of CT from soluble leaf protein. Animals adapt to diets containing high concentrations of CT by increasing growth hormone secretion, which stimulates protein synthesis to replace animal (i.e., gut wall) proteins precipitated by excess tannins and increases N retention. Cyanogenic glycosides pose no nutritional problems in legumes grown in New Zealand, due to selection for low HCN release. Red clovers grown in New Zealand contain high concentrations (0.6%-1.4% DM) of formononetin, which has oestrogenic activity. Grazing of red clover immediately before and during mating depresses the ovulation rate of ewes; when grazed at earlier times of the year, it increases subsequent returns to service and barrenness, with the effect being cumulative throughout the ewes' productive lifetime. Attack by insects and fungi induces high levels of coumestrol production in lucerne, which depresses ovulation rate in grazing sheep. Plant selection for low formononetin content is recommended. Methods of regulating CT concentration in lotus are discussed, and recommendations are made for introducing CT into white clover leaves using genetic engineering techniques. A key factor with CT is regulation of concentration at low levels uniformly distributed throughout leaf and stem tissue to produce nutritionally beneficial effects without the nutritionally detrimental effects produced by high concentrations.

Introduction

The thrift of stock grazing temperate legumes can be adversely affected by both primary or secondary plant metabolites (Reid 1973, Hegarty 1982).

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Soluble leaf protein appears to be the major cause of bloat (Mangan 1959). Secondary metabolites such as condensed tannins (CT), cyanogenic glycosides (CNG), saponins, oestrogenic compounds, and glucose derivatives of 3-nitropropanoic acid can cause a variety of effects from poor growth to reproductive upsets to death. The plant constituent may be active itself or may need to be converted to the active agent. That conversion may be facilitated by the rumino-reticular microorganisms; on the other hand the microorganisms may destroy the agent, thus acting as the animal's first line of defence. Reviews on bloat (M.D. Rumbaugh, "Breeding Bloat-Safe Cultivars of Bloat-Causing Legumes") and the effects of oestrogenic (W.J. Collins and R.I. Cox, "Oestrogenic Activity in Forage Legumes") and nitro-containing compounds (J.C. Burns, "Antiquality Factors in Temperate Forage Legumes") are given in these proceedings. The present paper will therefore focus mainly on the effects of tannins in fresh legume forages grown in New Zealand. Brief reference will be made also to cyanogenic glycosides and to the oestrogenic compounds in N.Z. legumes.

Tannins

Chemical properties

Tannins are phenolic compounds, and comprise both condensed and hydrolysable tannins (McLeod 1974, Reid et al. 1974). Only condensed tannins (CT) occur in N.Z. pasture species. CT are polymeric flavanols (gallocatechins and catechins). Upon hydrolysis, gallocatechins yield delphinidin (DP), whilst catechins yield cyanidin (CY). CT occur in the leaves and stems of sainfoin (Onobrychis viciifolia; MW 17,000-28,000) and of Lotus species (MW 6,000-7,100), in the flower petals only of white clover (Trifolium repens) (MW 8,500-9,100) and are non-detectable in lucerne and in grasses (Jones et al. 1976). Astringency, a measure of protein precipitated per unit weight of tannin, was in the order sainfoin<lotus<white clover, and increased with increasing DP content of the CT and decreased with increasing MW (Jones et al. 1976).

During disintegration of plant material, such as chewing by animals, CT react by hydrogen bonding with proteins to form a complex. The condensed tannin:protein complex is stable and insoluble in the pH range 3.5-7.0, but is unstable and releases protein at pH <3.0 and at pH 8.0 (Jones and Mangan 1977). In New Zealand, condensed tannins in forage plants are routinely determined by the vanillin-HCl procedure (Broadhurst and Jones 1978). Barry and Forss (1983) devised a method for measuring free tannin, defined as CT not precipitated by high-speed centrifugation of finely mascerated fresh plants. By definition, this portion has exceeded the capacity of the plant to bind it and is available to react with other proteins such as those of rumen microorganisms and the gut wall. Henceforth, the use of tannin in this paper refers to condensed tannins (CT), and 'tannin-containing legume' to species in which CT are measurable in significant concentrations in the leaves, where they occur in specialised cells that are distributed randomly (W.T. Jones, personal communication).

Animal Nutrition and Health

Theoretically, CT should be able to increase amino acid supply in ruminants fed fresh forages, as the range where the tannin:protein complex is insoluble includes rumen pH (5.5-7.0); the pH where protein is released by the complex corresponds with pH in the abomasum and small intestine. Because of the precipitation of forage proteins at rumen pH, legumes containing substantial concentrations of CT in leaves and stems are also bloat resistant (Jones et al. 1973). Although CT in Trifolium species are highly astringent, bloat occurs in cattle consuming these fresh forages because of the physical separation of the parts containing CT (flower petals) from soluble leaf proteins which induce bloating.

Polyethylene glycol (PEG: MW 3,350) forms a soluble complex with condensed tannins (Jones and Mangan 1977), and this principle can be used to either prevent protein reacting with condensed tannin or to displace protein from a pre-formed tannin:protein complex.

Factors Governing Condensed Tannin Concentration

In this paper, Lotus pedunculatus refers exclusively to 'Grasslands Maku', a tetraploid cultivar selected to suit N.Z. conditions (Armstrong 1974).

CT concentration in Lotus pedunculatus is increased when the plant is grown under conditions of environmental stress. When grown in high-fertility soil under warm conditions, CT concentration was 2%-4% DM, increasing to 8%-10% DM when grown in low-fertility acid soils under cold conditions (Barry and Forss 1983). On the low-fertility soils, CT content was reduced by fertiliser addition (table 1) and was negatively correlated with DM yield ($r=-0.94$; $p<0.001$).

Cultivars of Lotus corniculatus contain lower concentrations of CT (0.2%-3.0% DM; Ross and Jones 1983; Lowther, Manley and Barry, unpublished data) than does Lotus pedunculatus. Leaf tannin content in Lotus corniculatus is controlled by a single dominant gene, and tannin content is strongly and negatively related to HCN production from cyanogenic glycosides (Dalrymple 1982, Ross and Jones 1983). John and Lancashire (1981) reported CT in sainfoin (cultivar Fakir) to be 6% of DM.

Within the range 0%-9% DM of total CT, free CT comprised 9% of total for mascerated Lotus pedunculatus and 3% of total for mascerated sainfoin (T.N. Barry and T.R. Manley, unpublished data).

Influence of CT on Feeding Value

In this review, feeding value is defined as the animal production response to grazing a defined forage and is equal to voluntary DM intake x nutritive value/DM (Ulyatt 1973). Feeding value will be measured as liveweight gains of growing sheep, whilst digestion of nutrients in the rumen and post-ruminal regions of the digestive system will be used as indices of nutritive value. For young sheep grazing pure legume species grown in high fertility soil (table 2), feeding value of sainfoin (Onobrychis viciifolia) and lotus (Lotus pedunculatus) was superior to that of perennial ryegrass (Lolium perenne), red clover (Trifolium repens) and lucerne (Medicago sativa), but slightly inferior to that of white clover (Trifolium repens). The Lotus pedunculatus used can be classified as low tannin, because it was grown under warm conditions on a high-fertility soil. Thus, under these conditions, there is no evidence of CT causing toxic effects in either sainfoin or lotus.

Young sheep grazing areas of hill-country tussock oversown with either Lotus pedunculatus or white clover showed much lower rates of liveweight gain (table 3), which was increased by daily polyethylene glycol (PEG) drenching (MW 3,350) for lambs grazing lotus but not white clover. Thus, CT concentrations of approximately 8% DM in lotus can be classified as anti-nutritional.

Table 1 - Condensed tannin content of primary growth Lotus pedunculatus grown at a low soil fertility site as affected by phosphorus (P) and sulphur (S) fertiliser application

Fertiliser S (kg/ha/annum)	0			50			
Fertiliser P (kg/ha/annum)	0	10	40	0	10	40	SED
DM yield (kg/ha)	5	23	76	83	531	575	88.8
Condensed tannin (% DM)	8.6	9.2	8.5	8.0	5.1	5.4	1.49
Total N (% DM)	3.44	3.31	3.63	3.96	4.52	4.83	.351
Total S (% DM)	.12	.15	.19	.25	.26	.27	.028
Total P (% DM)	.10	.24	.40	.24	.29	.40	.037

Barry and Forss (1983). Soil pH was 4.7.

Table 2 - Growth of young sheep grazing pure species plots grown under high soil fertility conditions

Species	RFC[1] / structural CHO	Lignin (% DM)	Condensed tannin (% DM)	Liveweight gain (relative)	Liveweight gain (g/d)
Huia white clover	1.3	2.5	T	100	190-354
Fakir sainfoin	1.0	4.8	6.0	97	182-230
Maku lotus	0.8	11.6	2.0	87	153-315
Wairau lucerne	ND	ND	0	78	123-267
Hamua red clover	ND	ND	T	78	127-234
Ruanui ryegrass	0.3	2.0	0	52	88-198

[1]Readily fermentable carbohydrate (CHO) = soluble sugars + pectins; ND = not determined; T = trace amounts.

Source: John and Lancashire (1981).

Table 3 - Responses to daily drenches of polyethylene glycol (PEG; MW 3,350) in growing sheep grazing hill country tussock areas oversown with either Maku lotus or a mixture of white and red clover

Experiment No.	Legume	Condensed tannin (% DM)		Liveweight gain (g/d)		SED
		Total	Free	Water	PEG	
1	lotus	7.6	0.8	125	166	1.67
2	lotus	8.9	.7	27	70	.92
	clover	<.1	ND[1]	28	26	.92

[1]Non-detectable.

Mean initial liveweight was 36.0 and 25.5 kg in experiments 1 and 2, and daily quantities of PEG administered were respectively 100 and 75 g made up to 200 ml in water.

T.N. Barry (unpublished data).

Voluntary Intake. At the Invermay Centre, we have been defining effects of lotus CT on voluntary intake by studying intake responses to spraying with PEG (MW 3,350). The PEG binds a portion of the tannin, and the PEG-tannin complex is assumed to be quantitatively excreted in the faeces. The technique is thus assumed to be studying effects attributable to CT. When the total reactive CT content of lotus was reduced from 6.3% to 0.7% DM by PEG spraying (table 4), voluntary intake of metabolisable energy (ME) was increased 44% and the digestibility of structural carbohydrate (CHO) was increased 13%. These observations show that a CT concentration of 6% DM restricts both voluntary intake and probably rumen CHO digestion in sheep fed lotus. No comparable information is available for sainfoin, but the high feeding value recorded for this legume (table 2) suggests the voluntary intake of sheep is not restricted by CT.

Sites of CHO and Protein Digestion. Using *Lotus pedunculatus* containing 4.0% and 10.0% of CT, Barry and Manley (1984) found that CT depressed ruminal digestion of water-soluble CHO, pectins, and hemicellulose, thus confirming results from the dietary PEG addition studies. Conversely, Ulyatt

Table 4 - Voluntary intake and apparent digestibility of lotus as affected by reducing the total reactive condensed tannin (CT) content through spraying with polyethylene glycol (PEG; MW 3,350)

	Water-sprayed	PEG-sprayed	SED
Total reactive CT (% DM)	6.3	0.7	
Free condensed tannin (% DM)	.54	.05	
Apparent digestibility			
Cellulose (%)	52.7	57.9	2.62
Hemicellulose (%)	50.6	58.9	2.01
Voluntary intake (MJ ME/kg$W^{0.75}$/d)	.48	.69	.097

Barry and Duncan (1984).

and Egan (1979) found that 6% DM of CT in sainfoin did not impair any aspect of rumen CHO digestion, compared with predicted values for non-tannin containing fresh forages.

In figure 1, non-ammonia N (NAN) flow at the duodenum per unit of total N eaten (DN) has been plotted as a function of CT concentration (C) for a range of N.Z. fresh forages fed to sheep at similar total N intakes (approx 28 g/day). For the non-tannin-containing forages, white clover, short rotation and perennial ryegrass, duodenal N flow was substantially less than N intake, as a consequence of the high ruminal degradation rate of fresh forage proteins (70%; Ulyatt et al. 1975) and the subsequent absorption of ammonia from the rumen. In contrast, increases in CT within the range 0.25%-10.6% DM for *Lotus corniculatus* and *Lotus pedunculatus* produced a linear increase in DN ($r=0.997$; $P<0.05$), with predicted duodenal NAN flow being equal to total N intake at a CT concentration of 4.1% DM. At a constant dietary CT concentration, the CT in sainfoin were less effective than those in lotus for increasing duodenal protein N flow.

Calculated absorption of amino acids from the small intestine as a proportion of ME intake was greater for low- and high-tannin *Lotus pedunculatus* (29%) (Barry and Manley 1984) and sainfoin (25%) (Ulyatt and Egan 1979) than for perennial ryegrass and white clover (17% and 20% respectively) (MacRae and Ulyatt 1974). This confirms the beneficial effect of CT for increasing amino acid supply, and shows the lower MW lotus tannins to be more effective in this regard than the higher MW sainfoin tannins.

Animal Adaptation to High-Tannin-Containing Lotus. Responses in liveweight gain to daily PEG drenching (75 g; MW 3,350) in lambs grazing high-tannin lotus (8%-10% DM) for 5 weeks were greater in animals that had not previously grazed lotus (unconditioned sheep; 103 v 45 g/day) than in animals that had previously grazed high-tannin lotus for 8 weeks (conditioned sheep; 81 v 68 g/day; T.N. Barry, unpublished data). Thus, sheep adapt to the high tannin concentration to some degree, as indicated by the significant interaction ($P<0.05$), and that in the absence of PEG, growth rates were greater for conditioned than for unconditioned sheep.

Indoor feeding experiments using a range of PEG-sprayed *Lotus pedunculatus* forages (9.5, 4.5 and 1.4% DM as CT) fed to growing sheep at hourly intervals (750μg DM/d) have yielded a linear relationship between plasma growth hormone (GH) concentration (μg/l) and forage condensed tannin concentration (CT; % DM).

$$GH = \underset{\pm 0.402}{1.66} + \underset{\pm 0.065}{0.32}\ CT \qquad r = 0.980^{*}$$

No other hormone was affected by changing CT concentration (T.N. Barry and C. Redekopp, unpublished data), and it therefore appears that sheep respond to diets containing high concentrations of lotus tannins by increasing GH secretion.

Cyanogenic Glycosides

Cyanogenic glycosides (CNG) are esters of an aglycone and a sugar, which is generally D-glucose. During disintegration of the plant material, the glycoside is hydrolised and the aglycone undergoes re-arrangement to yield hydrocyanic acid (HCN). The chemical structure, synthesis, distribution, and concentration of CNG in temperate legumes have been described in detail by Tapper and Reay (1973). Two CNG's, lotaustralin and linamarin, occur in significant amounts in white clover (*Trifolium repens*) and in *Lotus* species in N.Z. pastures, and HCN concentrations of 14-1,760 ppm dry matter have been reported in white clover and of 70-4,500 ppm in *Lotus* (Butler 1965). Absorption of HCN from the stomach is rapid. Signs of toxicity include cessation of eating, depression, staggering, collapse, dyspnoea, chronic convulsions and death (by inactivation of the cellular cytochrome oxidase system). Toxicity problems caused by HCN depend upon the concentration of glycoside in the plant and the rate of release of HCN from the glycoside. Coop and Blakely (1949) calculated that grazing sheep

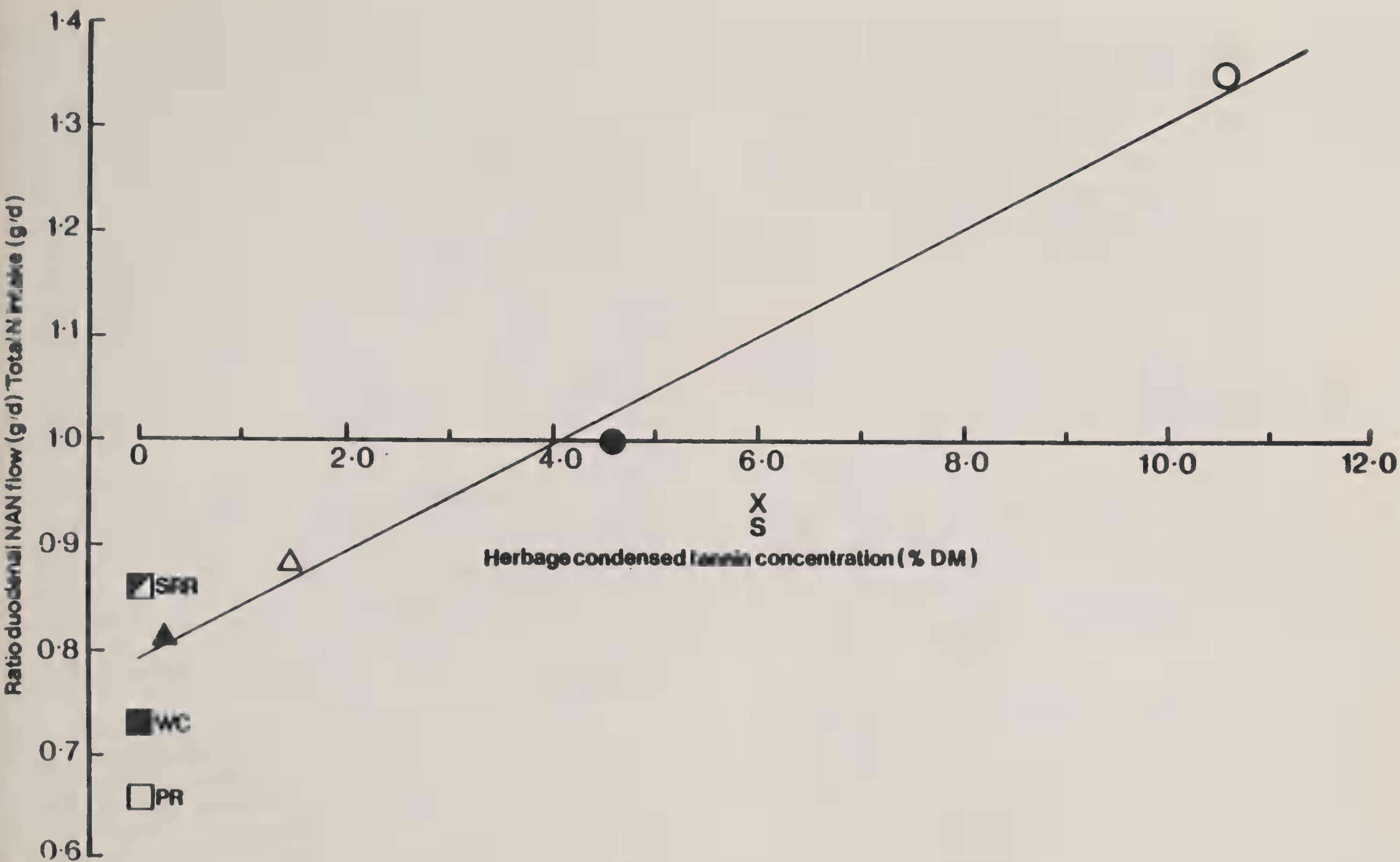

Figure 1--The quantity of non ammonia nitrogen (NAN) flowing at the duodenum per unit of total N consumed in sheep fed fresh forage diets (approx. 28 g N/day) grown in New Zealand. The data are plotted as a function of forage condensed tannin concentration. ▲ Δ low and high tannin cultivars of Lotus corniculatus (John and Lancashire 1981); ● o low and high tannin Lotus pedunculatus (Barry and Manley 1984); x S sainfoin (Ulyatt and Egan 1979). Regression line refers to lotus species only. Data are compared with the non-tannin-containing species white clover (WC ■), perennial ryegrass (PR □) and short rotation ryegrass (SRR ◪).

will tolerate 15-50 mg HCN/kg BW/day, that is, up to 20 x the acute minimal lethal dose (2.4 + 0.2 mgm HCN/kg BW, given as KCN). Gurnsey et al. (1977) reported death of a cow fed white clover containing 0.10% HCN via a rumen fistula; Coop and Blakely (1949) regarded a concentration of 0.09% to be highly dangerous and suggested that 0.07% should be the upper limit in new cultivars. HCN is also metabolised to inorganic thiocyanate ion by the liver, which is a goitrogen. Cultivars of white clover in current use in N.Z. agriculture have been selected for low rates of HCN production. Problems caused by HCN release are no longer apparent in animals grazing them due to this factor and also that the white clover component in ryegrass/clover pastures seldom exceeds 25% of the DM and is frequently in the range 5%-15% of the sward DM.

Oestrogenic Substances

Two classes of compound, isoflavones and coumestans, occurring in legumes are oestrogenic and can cause reproductive disorders and infertility in grazing animals, more commonly in sheep than cattle (see Schutt, 1976, for review). Isoflavones occur typically in the clovers; their concentration is low in white clover but high in T. pratense (red clover) and can reach 5% of DM of T. subterraneum (subterraneum clover) (Schutt 1976). Formononetin is the most important isoflavone; it is not oestrogenic itself but is converted in the rumino-reticulum to the weakly oestrogenic equol, which is the biologically active agent. By contrast the other isoflavones, intrinsically active, are converted to inactive forms.

Coumestans, the second class of compounds, are present in only small amounts in healthy plants but can increase very markedly in white clover and lucerne (Medicago sativa) in response to attack by fungi (Loper and Hanson 1964, Wong and Latch 1971) or insects (Loper 1968, Kain and Biggs 1980). Smith et al. (1979) have reported a negative, linear relationship between coumestan (CM; ppm) concentration in lucerne and ovulation rate (OR) in ewes.

$$OR = 1.38 - 0.004CM \quad r = -0.97^{***}$$

In New Zealand significant infertility in sheep due to phyto-oestrogens occurs only in association with grazing lucerne or red clover. Reproductive inefficiency of ewes grazing lucerne has been known for 25 years (Coop and Clark 1960) and has been associated with fungal infection of the plant (see Smith et al. 1979). Effects of grazing red clover on the reproductive performance of ewes have been reported by Kelly et al. (1979, 1980), Kelly and Shackell (1982), Shackell and Kelly (1984 and unpublished) and can be summarised as follows:

Formononetin concentration in the cultivars 'Pawera', 'Hamua' and 'Turoa' (0.6%-1.4% DM) is above the "safe" level (0.3% DM). Grazing of Pawera containing 1.0% and 0.7% DM as formononetin for 25 and 10 days, respectively, during mating depressed ovulation rate by 50% and 20%, increased returns to service, and reduced lambing percentage. Grazing of Pawera for 4-month periods during summer, terminating one month prior to mating, had no effect upon ovulation rate, but increased both returns to service and barrenness in both the following and in future matings. Ewe lambs grazing Pawera from 3-7 months of age suffered no depression in fertility when mated at 1-1/2 years. Making the legume into field-cured hay reduced formononetin concentration to safe levels.

Discussion

In an evolutionary sense, secondary compounds have been proposed as a chemical defence against predators to ensure that over-grazing did not occur (Hughes 1970). In modern agricultural systems, creating less toxic cultivars by either conventional breeding or genetic manipulation is a logical recourse.

Condensed Tannins

Effects attributable to the presence of CT in temperate legumes grown in New Zealand can be classified as both detrimental and beneficial. Detrimental effects include depressions in voluntary intake and ruminal CHO digestion, whilst beneficial effects are reduced ruminal protein degradation, reducing the risk of bloat and considerably increasing amino acid absorption.

Mechanism of Condensed Tannin Action. The most important properties of CT in determining whether nutritional effects are likely to be detrimental or beneficial are considered by us to be firstly the total concentration and secondly reactivity with proteins, which in turn depends upon MW and DP content. Thus, lotus tannins that are of low MW and high reactivity with proteins (Jones et al. 1976) are very efficient at increasing amino acid supply in sheep but cause reduced ruminal CHO digestion (Barry and Manley 1984) and reductions in voluntary intake (Barry and Duncan 1984). Barry and Forss (1983) suggested that the actual detrimental factor was the content of free tannin, which is strongly correlated to the concentration of total tannin; this could conceivably react with and precipitate proteins of the gut wall and extracellular CHO-degrading enzymes secreted by rumen bacteria. Alternatively, the high MW lower reactivity condensed tannins in sainfoin were less efficient than lotus tannins at increasing amino acid supply but did not cause any depression of rumen CHO digestion. Free tannin is less for sainfoin (3% total) than for Lotus pedunculatus (9% total).

An established function of growth hormone (GH) is a generalised increase in the rate of protein synthesis (Trenkle 1980). It therefore seems that the animal responds to high dietary concentrations of condensed tannins attacking and inactivating proteins of the gut wall by increasing GH secretion, which in turn stimulates replacement protein synthesis. Such a repair mechanism seems feasible, and a similar increase in GH secretion has been observed in sheep fed brassica diets which produce the protein-inactivating compound dimethyl disulphide (Barry et al. 1984). The effect of dietary condensed tannins in raising GH secretion also explains instances where amino acid absorption has been similar, but nitrogen retention greater, in sheep fed tannin-containing than non-tannin-containing fresh forages (Ulyatt and Egan 1979, John and Lancashire 1981).

Tannin-Containing Forages in Agricultural Systems. Because of its lower fertiliser requirements than white clover, the use of Lotus pedunculatus to oversow large areas of low pH (4.4-4.9) tussock grasslands in the South Island is likely to continue. If animal adaptation to this legume is confirmed in future trials, the best use of the high-tannin (8% DM) forage produced is likely to be in grazing systems where animals are allowed access to Lotus pedunculatus for the complete duration of the grazing season (4 months) rather than being transferred at intervals between tannin-containing and non-tannin-containing forage.

Other alternatives for hill country pastures of low soil fertility are use of Lotus corniculatus cultivars that contain lower concentrations of CT, but these are only likely to establish and grow where soil pH exceeds 5.0. The CT content of Lotus corniculatus has a heritability of 53% (Dalrymple 1982). Thus, an alternative for use on more acid soils is to establish if CT content is also highly heritable in Lotus pedunculatus and to select for lower concentrations of CT when grown under these conditions with low fertiliser inputs.

Barry (1982) concluded that amino acid supply was limiting output of high-producing ruminants fed ad libitum on fresh forages grown on high-fertility soils. Introduction of CT into leaf and stem tissue of legumes grown under these conditions would therefore be nutritionally beneficial and also eliminate the risk of bloat. Sainfoin and Lotus

pedunculatus are unsuitable for growth under these conditions in New Zealand (Brock and Charlton 1978). Alternatives proposed by us are firstly identification of regulatory genes that prevent expression of CT in leaf and stem tissue of clovers. However, it should be noted that because of the low MW and high DP content of white clover CT, high plant concentrations can be expected to cause the same nutritional problems as high concentrations of CT in lotus. Secondly, a safer procedure for use over a range of environments would seem to be identification of CT-producing genes in sainfoin and their transfer to white clover using genetic engineering techniques. To achieve success, it will be necessary to understand in detail the biochemistry of CT production and metabolism, its regulation and the genetic encoding of the regulatory system. More will need to be known concerning the limits for beneficial concentration of the particular CT in the particular legume in various environments. Further, if, as seems probable, GH is involved in the metabolism of CT by ruminants, the basis of the CT-GH interaction will need to be established.

Cyanogenic Glycosides and Oestrogenic Activity

As cyanogenic glycosides are currently not posing any problems with N.Z. legumes, the only comment that can be made is that new selections should be screened for HCN release to ensure that this situation continues into the future. Because of the high formononetin content, pure swards of N.Z. red clovers should not be grazed by reproducing ewes and should instead be grazed by fattening lambs, ewe lambs in their first year, or made into hay.

Future Research Needs

1. Red clover cultivars in use in New Zealand should be selected for low formononetin content, as is currently being done at Grasslands Division DSIR.

2. There should be some re-selection of Lotus pedunculatus (cv Grasslands Maku) for low CT concentration when grown in acid low-fertility soils, but this should not be at the expense of breeding for improved cold hardiness and frost tolerance.

3. Methods should be explored for introducing CT into leaf and stem tissue of white clover using genetic engineering techniques. As environmental effects, notably changes in soil fertility, are likely to result in a range of CT concentrations being produced, transfer of the high MW sainfoin tannin is preferred. This will reduce forage protein degradation in the rumen without depressing rumen carbohydrate digestion. If lower MW tannins are transferred from Trifolium arvense, it will be necessary to restrict their concentration to 2%-4% DM.

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Discussion

Marten: Relationship of voluntary intake to tannin. Is there any effect on the palatability in different individual plants?

Barry: Only one genotype of *Lotus pedunculatus* (cv Grasslands Maku) has been used in New Zealand. There has been no attempt to look at individual plants.

Steele: In some of the South Island pastures based on either lotus or white clover grown on acid low fertility soils, the grass has developed more successfully with white clover than with lotus. We know tannins prevent or slow down breakdown of N in soils (Vallis). Is the concentration of tannins in lotus roots as high as in the shoots? If tannins were transferred into white clover, would the same effect happen?

Barry: In *Lotus pedunculatus* (cv Grasslands Maku) grown in acid low fertility soils, we find the same concentration of condensed tannins in root as in shoot tissue (8% DM). I agree with you that this probably slows breakdown of N in the soil and probably is a factor in grasses developing less successfully with lotus than with white clover on these soils. If tannins were transferred to white clover, I think it desirable to aim for a low concentration to minimize this effect.

Easton: The most obvious source of tannins is within a species or genus. Why go to sainfoin tannins rather than *Trifolium arvense*?

Barry: The molecular weight (MW) of tannins in *T. arvense* and lotus are similar (8,000). The reason for suggesting sainfoin is that its tannins are a higher molecular weight (22,000), and if transferred into new plants, high concentrations will have a less detrimental effect on rumen carbohydrate digestion than the lower MW tannins. Use of sainfoin-type tannins would therefore be best in situations where changes in environment resulted in large fluctuations in tannin concentrations.

Brougham: Keep things in perspective. Despite drawbacks of tannins, lotus has allowed development of large areas of low-fertility tussock that couldn't be developed before. Bringing in any new plant often involves changes in other factors within farming to suit the new cultivar.

Minson: Would you like to speculate on adaptation of animals to tannins in lotus?

Barry: As a guess, the rumen microbes adapt and this could lead to greater intake.

Lancashire: Alan Harris has evidence that sheep exposed to formononetin in red clover over a period of years show reduced effects on fertility in the third year.

Barry: Western Australian evidence suggests that the effects of formononetin are accumulative.

Lowther: Growth rates of animals on Maku lotus are reasonable but could be better if tannin levels were lowered. However, low voluntary feed intake in sheep shouldn't be a worry as lotus is quite satisfactory as the best alternative for South Island high country. Sheep shouldn't be left too long on lotus for agronomic reasons. This highlights the need for collaboration between agronomists and nutritionists to avoid rejection of lotus by farmers.

Antiquality Factors in Temperate Forage Legumes in the United States

J.C. Burns[1]

Abstract

Secondary compounds in plants are products formed from side reactions of primary metabolites. They may be important in the survival of plants in a competitive environment. Certain of these secondary compounds impart antiquality characteristics to forage plants, causing depressed animal performance when forage is consumed. Depending on the compound in question, its concentration in forage, the level of forage consumed, and the animals' ability to degrade or excrete the substance, an acute or chronic response may be exhibited. Both conditions are costly to the livestock industry. The secondary compounds present in the more important legumes grown in the United States are discussed. In instances, antiquality compounds in less important legumes are also cited. Distinction is made between those constituents that cause acute toxicity and death compared with those that cause chronic conditions or that are deterrents to maximum animal response.

Introduction

The primary metabolites in plants are generally of protein, or RNA and DNA synthesis, energy production, and basic cellular structures. Side pathways from primary synthesis result in products that are apparently not essential to primary metabolism but accumulate and become a part of the plant structure or soluble constituents. Tissue differentiation as plants mature alters forage quality through reductions in dry matter digestibility, intake, or both. Further, specific compounds can accumulate in plant cells in sufficient quantities to adversely influence animal response. Important secondary compounds have the alleochemic characteristic of being synthesized by one organism and affecting another by either stimulation or inhibition (Barnes and Gustine 1973). Further, such compounds remain in a dynamic state of change (Barz and Köster 1981). From the viewpoint of forage utilization, both physical and chemical factors can be considered antiquality constituents. Discussed are the formation, occurrence, and implication of antiquality constituents present in the important U.S. forage legumes listed by Wheeler (1950). Focus is directed to the plant aspect and pertinent literature is cited. The animal aspect of toxins is discussed elsewhere (see Dennis J. Minson and Mervyn P. Hegarty, "Toxic Factors in Tropical Legumes," earlier in these proceedings).

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General Pathways and Effects from Antiquality Constituents

An abbreviated pathway showing the formation of both structural and secondary (allelochemic) compounds formed as side products from primary metabolism is presented in figure 1. While certain constituents cause drastic responses (including death) when consumed by animals, others (including the fiber fractions) are rather subtle and are detected only as reduced animal responses. Slight alterations in intake, digestibility, or both are difficult to detect but can have a pronounced impact on animal performance (Burns 1978). Knowledge of "threshold levels" of antiquality constituents in plants and of subsequent animal responses is often inadequate.

Structural Constituents as Antiquality Factors

Increased cell wall constituents with advancing maturity and differences among species in cell wall concentration are documented for many forage species (Moore and Mott 1973). Cell wall concentration is generally negatively associated with dry matter digestibility, dry matter intake and animal performance (Dehority and Johnson 1961). However, cell wall concentrations in legumes are less than those in grasses.

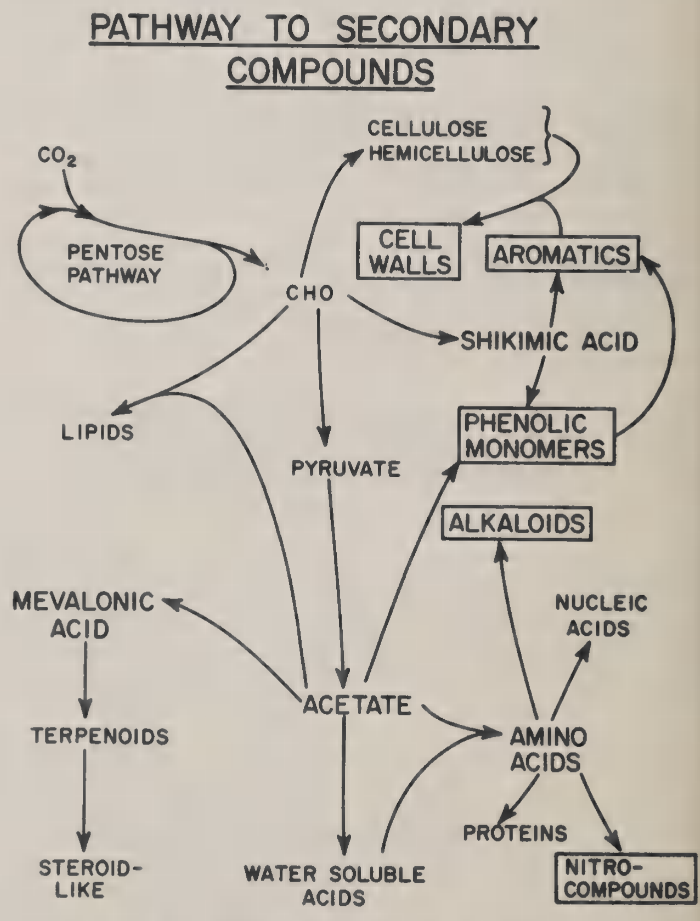

Figure 1—An abbreviated biochemical pathway showing the relationships among antiquality constituents. Boxed constituents have generic characteristic.

Legumes have several morphological and anatomical characteristics that partially negate the effect of secondary wall thickening which depresses forage quality in grasses. Legumes such as white clover (Trifolium repens L.) have extended petioles bearing the leaflets and the inflorescence. Both the petiole and leaflets are highly digestible over a wide range of maturities, and the less digestible stem-like portion is rarely defoliated because of its proximity to the soil surface. In contrast, erect growing legumes such as alfalfa (Medicago sativa L.) and lespedeza [Lespedeza cuneata (Dumont G.) Don] have leaflets attached to a substantial stem by short petioles. Defoliation by animals or mechanical harvesting removes both leaves and stems leading to forage with generally higher cell wall concentrations and reduced animal performance.

The anatomical features of dicotyledonous legumes that offset their generally high concentration of lignin, relative to monocotyledonous grasses, is secondary lignin deposition along a central cambium compared with the dispersal of fiber bundles enveloped by lignified sclerenchema throughout the cortex of grasses (Esau 1960). The lignin of legumes tends to be more inert and considered "core lignin" compared with the ligno-cellulose complex that forms in grasses (Jung and Fahey 1983b). In addition, the pathway of lignin formation in dicotyledonous plants gives rise to different basic phenolic monomers in the lignin moiety than that found in monocotyledonous plants. These compositional and mode of deposition differences appear to relate to forage quality in that legume lignin is more condensed and potentially less reactive than is grass lignin (Gorden 1975). For example, at similar fiber digestibility, legumes have higher lignin concentrations (Ghose and King 1963), but grass lignin on a per unit basis has a greater depressing effect on cell wall digestion than does legume lignin (Van Soest 1975). Thornton and Minson (1973) reported 28% greater voluntary intake from legumes (six species) compared with grasses (eight species) at equal digestibilities. Higher intake from legumes was attributed to a 17% shorter rumen retention time and a higher rumen dry matter density (14% more organic matter in the rumen digesta) of the legume diets. Although lignin and associated structural constituents of legumes resist breakdown in the rumen, they present far less of a physical barrier to rate of digestion than that noted for grasses; thus legume cell walls are only a moderate antiquality factor.

Secondary Compounds as Antiquality Constituents

Knowledge about the biological importance of secondary compounds is limited (Bell 1981). A partial understanding exists for only a few compounds which inflict striking consequences when consumed in toxic quantities. Many secondary compounds cause protective plant x animal, plant x plant, plant x insect, and plant x microbial interactions (Bell 1981). Consequently, secondary compounds are of prime importance in establishment, persistence, and survival of specific plants in an environment shared by other organisms.

Acute Toxicity (Poisoning)

The species of the legume genera that serve either as seeded pasture for grazing or as part of the natural vegetation in rangelands that have caused severe animal disorders or death are listed in table 1. The majority of these plants represent a constituent of the flora from the western rangelands of the United States. Most important are the Astragalus species. Some species are known as locoweeds, others as milkvetches, and others as selenium accumulators (when grown on high-selenium soils). Although not considered as a natural toxin, selenium replaces sulfur in sulfur-containing amino acids to form toxic selenium compounds (Williams and James 1978). Locoweed is found from North Dakota to Texas and west (James et al. 1980), while milkvetches occur largely from Central Montana south to Colorado and into Arizona and west. Several species of lupine also cause toxicity and occur in North and South Dakota and south through Colorado and New Mexico and west.

Species of Indigofera are receiving consideration in Hawaii and the Deep South and Southwestern United States as potential grazing or hay crops. While this tropical genus has desirable forage and soil-building characteristics, many of the species contain aliphatic nitro compounds in toxic concentrations (Williams 1981). Both the Medicago and Trifolium genera appear in the table because of their frothy bloat characteristics that may cause substantial death losses to ruminants. The other genera in table 1 represent species of lesser importance which have acute toxicity potential.

Chronic Toxicity

Death losses associated with acute toxicity are devastating when outbreaks occur (Williams et al. 1979). Yet chronic conditions that cause submaximal performance when antiquality constituents are consumed may be even more costly, being more prevalent than acute toxicity and resulting in loss of feed conversion efficiency. Such low-level toxicity is subtle and seldom detected except after extended periods of no weight gain or weight loss.

Nitro Compounds

Aliphatic nitro compounds have been found in the genera Astragalus (William and Barnby 1977), Indigofera (Williams 1981), Lotus (Williams 1983), and Coronilla (Gustine 1979). When consumed in adequate quantities, these compounds can be highly toxic to both monogastrics and ruminants. The Astragalus species from milkvetches have received considerable study and provide insight into the complexity of the problem. The first nitro compound isolated was a β-D-glucoside of 3-nitro-1-proponol, miserotoxin, which is catabolized in the digestive tract of ruminants to the highly toxic 3-nitro-1-proponol (3-NPOH). Absorption into the circulatory system affects the central nervous system, especially the area of the brain that controls coordination and automatic responses. Most animal deaths from Astragalus are associated with plants containing this toxin. Other Astragalus milkvetches contain cibarian, hiptagin, and karakin which are catabolized to 3-nitropionic acid (3-NPA). The 3-NPA is far less toxic mg^{-1}, because the former is either more slowly released by the plant into the rumen or more slowly absorbed by the animal or both. There is evidence (Gustine

Table 1 - Summary of major legumes in the United States containing toxic plant constituents from which animal deaths have been reported[1]

Plant-Species #	Type[2]	Toxin	Source[3]	Condition	Situation
Acacia berlandieri (Guajillo)	Shrub	N-Methyl-β-phenylethylamine	V, F	Ataxia (limber leg) prostration and death (starvation)	Consume 15 times weight over several months
Astragalus species: Group I--many (Poison vetches)	Herb.	Selenium accumulation	V	Blind staggers, alkali disease	Consuming plant for week (+) under 200 ppm in forage
Group II[4]--11 + (locoweeds)	Herb.	Unidentified	V	Neurological damage, habituation, emaciation, abortion and birth defects	Consume 90% of weight over 2 weeks
Group III--5 + (Timber milkvetch)	Herb.	β-D-glucoside of 3-nitro-1-propanol (Miserotoxin) and a glucoside of 3-nitropropionic acid	V	Cracker-heel disease--rough coat, irregular gait, hind feet knock together, respiratory distress, death	Consume plant for less than 1 week
Crotalaria species	Herb.	Pyrrolizidine alkaloids, Monocrotaline	S, V	Chronic, appetite loss, poor condition, blood in feces, lesions, death	1.4 kg seed; 55% of weight fed over 2 months; LD_{50} = 261 mg kg^{-1}
Indigofera endecaphylla (creeping Indiago)	Herb.	β-nitro-propionic acid; NO_2	V	No weight gain, reproductive problems, premature-weak calves or dead calves	Sole diet for 25 days
Lathyrus species--9 (vetchlings or pea)	Herb.	a. L-alpha, gamma-diaminobutyric acid b. β-aminopropionitrile	S S	a. Hyperexcitability and death b. Skeleton deformation	
Lotus corniculatus	Herb.	Cyanogenic glucoside	V	Death	Sole Diet
Lupinus species--11 (Lupine bluebonnet)	Herb.	Alkaloid anagyrine	S, V	Rough, dry hair coat, labored breathing, depression, nervousness, death; crooked calf disease--misaligned joints, twisted bones and wiry neck	0.2 to 5% of animal weight day^{-1} or less amount eaten 3 to 7 days
Medicago sativa (Alfalfa)	Herb.	Saponin-protein complex	V	Chronic, subacute or acute frothy bloat	Rapid intake of leafy forage
Prosopis juliflora (Mesquite)	Shrub-Tree	(Unbalanced diet)	S	Rumen stasis, impaction	Extended time period (8 to 12 months)
Trifolium species--2 (clovers)	Herb.	Saponin-protein complex	V	Chronic, subacute or acute frothy bloat	Rapid intake of leafy forage
Vicia villosa (Hairy vetch)	Herb.	Not identified	S, V	Rough hair coat, skin lesions, loss of appetite and weight.	Sole diet

[1] Taken from J.M. Kingsbury 1964, L.F. James et al. 1980, R.F. Keeler 1978, and P.T. Hooper 1978.
[2] Herb = herbaceous.
[3] V = vegetation; F = fruit and S = seed or bean.
[4] Plus oxytropis species.

1979) that 3-NPA is degraded in the rumen by micro-organisms. The concentration of 3-NPA and 3-NPOH differs greatly between two groups of Astragalus milkvetches, with the former accumulating up to 4 to 6 times more NO_2 g^{-1} than the latter. At highest accumulations, both species can be equally toxic (Williams and James 1978). Locoweed contains an organic poison, yet unidentified, that affects the central nervous system (Van Kampen et al. 1978). At the other extreme is cicer milkvetch (Astragalus cicer L.), which apparently contains no toxic compounds, has high quality and yields, and is a potentially valuable forage legume (Townsend et al. 1978).

Chronic animal disorders frequently occur on ranges infested with 3-NPOH-containing Astragalus species that have 3 to 7 mg NO_2 g^{-1} of plant dry matter. Because of the low toxin concentration and the opportunity for animals to selectively graze other species, deaths do not occur, but animals are unthrifty and sustain permanent damage to their vital organs. The extent to which grazed plants with low concentrations of 3-NPOH and normal concentrations of 3-NPA adversely influence animal responses is not clear, but could be appreciable.

Crownvetch (Coronilla varia L.), although not widely used for forage in the United States, also contains nitro compounds with 3-NPA as the monoester, cibarian as the diester, and karakin as the triester (as found in Astragalus). However, season-long grazing trials have shown no adverse cattle responses; steer and calf daily gains averaged 0.47 and 0.96 kg (Burns et al. 1969, Burns et al. 1977). However, initial rejection can occur when animals are placed on crownvetch pastures. In a stall trial examining soluble inhibitors found in lespedeza and crownvetch, Burns et al. (1972) suggested that the rumen micro-organisms adapted to such compounds. Gustine et al. (1977) later showed that NPA esters (cibarian, coronarian, karakin, and coronillin) from crownvetch were hydrolyzed in 4 h by rumen micro-organisms to NPA and glucose. After 28 h, NPA was metabolized to unidentified products. These studies showed NPA could be detoxified in the rumen if levels did not exceed 1.0 mg ml^{-1} of rumen fluid. Concentrations of 3-NPA in crownvetch forage have not been reported above 12 mg NO_2 g^{-1} of dry matter (Gustine 1979). However, 3-NPA toxicity occurs in nonruminants where it is attributed to inhibition of succinate dehydrogenase and fumarase and the formation of methemoglobin from metabolic breakdown to nitrite ion (Gustin and Moyer 1981). Apparently, the lower toxicity of 3-NPA vs. 3-NPOH, the low concentrations of 3-NPA normally found in crownvetch forage, and possible metabolism of 3-NPA in the rumen prevents crownvetch from causing acute toxicity in ruminants.

Examination of the Lotus spp. showed no nitro compounds in commercial cultivars of birdsfoot trefoil (Lotus corniculatus L.). However, cultivars of Lotus pedunculatus L. presently being evaluated for productivity in the United States, had total forage 3-NPA concentrations ranging from 19 to 23 mg NO_2 g^{-1} of dry matter (Williams 1983). The use of L. pedunculatus in pasture mixtures is unlikely to cause acute poisoning if 3-NPA in the foliage does not exceed 25 mg NO_2 g^{-1}.

Nitro compound concentrations vary among cultivars and among plant parts in all three of the above genera. Leaves have highest concentrations and are generally double those of stems. Concentrations of 3-NPA in crownvetch leaves, petioles and stems averaged 12, 8, and 4 mg NO_2 g^{-1} of dry matter, respectively. Concentrations in leaves and stems of L. pedunculatus averaged 28 and 15 mg NO_2 g^{-1} of dry matter. Further, increased temperatures increased 3-NPA in both crownvetch and Astragalus spp., while exclusion of light reduced miserotoxin in Astragalus sp. (Parker and Williams 1974, Gustine 1979). Thus, concentrations of nitro compounds in forage dry matter would be expected to increase under midsummer conditions.

No cases of acute livestock poisoning have been reported from animals grazing crownvetch or L. pedunculatus, but 3-NPA levels in excess of 20 mg NO_2 g^{-1} of dry matter would likely result in a chronic condition after prolonged grazing (Williams 1983). The question of antagonistic effects from subclinical conditions on animal function and subsequent performance has not been adequately evaluated.

Aromatic Compounds

Soluble Phenolic Monomers. Phenolic monomers are formed through the shikimic acid and acetate-malonate pathways (fig. 1). The former pathway gives rise to p-hydroxy and the latter to m-hydroxy compounds. These monomers from the aromatic amino acids which are precursors of benzoic acid derivatives (C_6-C_1) of p-hydroxybenzoic, vanillic, syringic, salicylic, protocatechuic, and gallic acids (Jung and Fahey 1983b). Phenylalanine, tyrosine, and phenylpropionic precursors can be converted to phenylpropanoid compounds (C_6-C_3), which include p-coumaric acid, ferulic acid, and coniferyl alcohol.

Extracting soluble phenolic fractions from forage dry matter increased in vitro fermentation of both cellulose and protein (Jung and Fahey 1983a). Further, in vitro fermentation studies showed that additions of p-coumaric, ferulic, salicylic, and protocatechuic acids and vanillin reduced cellulose and starch disappearance (Jung and Fahey 1983a). The reductions were intensified linearly with increasing monomer concentrations. Salicylic and p-coumaric acids, vanillin, and protocatechuic acid decreased cellulose disappearance in the order listed. Vanillin was the most effective depresser of starch digestion. The influence of phenolics on fermentation was partially attributed to bacterial membrane damage, lysis of the bacteria, and release of the cell contents. Ferulic and p-coumaric acids and vanillin were found in the gastrointestinal tract of lambs fed either alfalfa or smooth bromegrass (Bromus inermis L.) hays (Fahey et al. 1980).

The extent to which phenolic monomers form hydrophobic coatings of protein (known to occur in tannin-protein complexes) or unavailable complexes with other nutrients is unknown (Jung and Fahey 1983b). The lack of knowledge about the role of phenolic monomers as possible antiquality constituents of forages requires further investigation.

Polymeric Phenols. Polymeric phenolic tannins are important antiquality constituents of sericea lespedeza in the United States. Tannins (categorized as aromatics in fig. 1) are contained in all parts of the plant, ranging from 120 g kg^{-1} dry matter in immature leaves to 18 to 26 g kg^{-1} in stems (Burns 1978). The greater concentration of tannin in leaves of sericea causes leaf quality to be inferior to that of stems (Cope and Burns 1974). Tannins have strong protein-binding properties which distinguish them from other polyphenolic compounds. They are composed of two broad groups: the hydrolyzable types, which frequently contain gallic acid units, and the condensed or catechin-types (Price and Butler 1980). Lespedeza contains the latter, which is known to impart the astringent or bitter taste to forage and to cause inhibition of celluolytic and pectinolytic enzymes (Lyford et al. 1967). Tannins are concentrated in the cell vacuole or separated from the protoplasm of the cell and released only when the integrity of the cell is disturbed.

The astringent and inhibitory characteristics of lespedeza tannin have been implicated in both reduced forage dry matter intake and digestion (Burns 1978). In a stall trial comparing daily dry matter intake or alfalfa and lespedeza hays, heifers fed alfalfa had higher intake (6.1 vs. 5.6 kg) and higher daily gains (0.65 vs. 0.49 kg), even though the fiber fractions (neutral and acid detergent fibers) were similar (Burns et al. 1972). In vitro dry matter disappearance (IVDMD) values greatly favored alfalfa (529 vs. 387 g kg^{-1}). The differences in animal responses and IVDMD were attributed to tannin concentrations.

Selection of low tannin lines increased IVDMD from 350 g kg^{-1} for common lespedeza to 400 g kg^{-1} for a low tannin line (Cope and Burns 1974). A low tannin lespedeza, AU LOTAN, released by Auburn University (Donnelly and Anthony 1980) averaged 50% less tannin (30 vs 61 g kg^{-1}) and 27% higher IVDMD than common strains. However, quality was still less than desired. Cope and Burns (1974) reported that fiber constituents also limited IVDMD of lespedeza. Recently, low tannin lines selected for high protein and sugar concentrations (low fiber) had IVDMD averaging (three summer harvests) 603 g kg^{-1} (Donnelly and Anthony 1983). Tannin concentrations in lespedeza are reduced by low light and low temperatures and increased by severe drought and maturity (Burns 1978). Consequently, tannin concentrations normally increase during the summer.

Although tannins are normally considered antiquality factors their protein-binding characteristics have also been beneficially used in the protection of proteins in ruminant rations against bacterial deamination in the rumen (Barnes and Gustine 1973).

Cyanogenic Glucosides

Both Trifolium and Lotus species general contain cyanogenic glucosides. White clover contains a mixture of two glucosides (linamarin and lotaustralin), and birdsfoot trefoil contains the latter (Barnes and Gustine 1973). While health problems or death from the glucosides have not been reported in the United States for either species, they can release potentially toxic quantities of HCN when plant tissues are disrupted. The mechanism involves the enzymatic cleavage of the glucoside (β-glucosidase) and the enzymatic (hydroxynitril lyase) release of the CN^- radical and the formation of HCN. HCN is readily absorbed into the blood and distributed to all body tissues. HCN acts by forming an inactive complex with cytochrome oxidase, which inhibits exchange of O_2 and causes asphyxiation at the cellular level.

Management or environmental factors that increase the glucoside in plants are high nitrogen availability, high nitrogen to low phosphorus ratios, drought, and reduced temperatures. Reduced levels of glucosides are associated with low fertility. Plant factors that increase glucoside formation are increased photosynthetic rate, reduced plant maturity, leafiness (leaves contain 25 times more glucoside than stems), and genetic makeup (Burns 1971).

The toxicity of the forage to animals is variable depending on animal size, selectivity in grazing, consumption rate, and capacity to tolerate and detoxify the HCN released in the rumen (Burns 1971). Generally, toxicity occurs within the first 20 minutes of grazing. A dose that provides 20 mg of HCN/100 g of fresh forage (Kingsbury 1958) or 1 g of HCN per 454 kg of body weight (Boyd et al. 1958) has been suggested as lethal. A 454 kg animal would have to consume about 5 kg of fresh forage (20 mg of HCN/100 g) to obtain 1 mg of HCN. This quantity can be easily consumed in the time noted above. Subtoxic concentrations can adversely alter rumen micro-organisms (Bell 1981). The extent to which subtoxic HCN levels can alter the physiological functions of the animal relative to animal performance, has not been clearly determined.

Alkaloids

The Lupinus genus contains the teratogen quinolizidine alkaloid "anagyrine" that has been shown to cause crooked calf disease (Keeler 1978). Acute symptoms are misaligned joints and twisted bones, spinal curvature, twisted neck, cleft palate, or a combination of these. In mild cases, deformity is confined to slight bowing of the forelegs. Pregnant cows are susceptible to the action of anagyrine only between the 40th and 70th days of gestation. Since anagyrine is highest in young growth and in seeds, the hazard of the disease is minimized by grazing lupine species either in early flower or postseed stages and before or after the critical period of gestation. However, "sweet" varieties have been developed that can be safely used for either grazing or for soil improvement (Edwardson et al. 1963).

Crotalaria species contain pyrrolizidine alkaloids that have caused losses in cattle and sheep from disease of the liver and occasionally of the lungs (Hooper 1978). Sheep are less susceptible than cattle, requiring 20 times more toxin to cause death. The active metabolites are the pyrroles, which vary when formed from the pyrrolizidine alkaloids, causing a broad range of toxic animal responses. The finding in sheep that ruminal microflora can detoxify the alkaloids could be

important in their differential sensitivity (Hooper 1978).

The extent to which the teratogen and pyrrolizidine-type alkaloids affect the performance of animals in low to moderate concentrations over a long period is not clear.

Other Compounds

Alfalfa and white clover are the major bloat-causing legumes in the United States, and both have estrogenic activity. The topic of bloat is discussed by M.D. Rumbaugh ("Breeding Bloat-Safe Cultivars of Bloat-Causing Legumes") and estrogenic activity is discussed by W.J. Collins and R.I. Cox ("Oestrogenic Activity in Forage Legumes") in these proceedings. Although discussion has been limited to antiquality constituents of primary plant origin, two fungal-related disorders deserve mentioning. Sweetclover [*Melitotus officinalis* (L.) Lam. and, *M. alba* Desr.] bleeding disease (hypoprothrombinemia) can occur when fungi develop during storage and interact with substrate (coumarin or cis-o-hydroxy cinnamic acid) in the sweetclover to form the blood anticoagulant dicoumaral [3,3' methylene bis (4-hydroxy coumarin)]. Consumption can cause animal losses from excessive internal bleeding (Casper et al. 1982).

Refusal by cattle to eat second-cut red clover after several feedings, excessive salivation, and toxic symptoms have been attributed to the presence of the alkaloid slaframine (1-acetoxy-6-amino-octahydro-indolizine) produced by the fungus *Rhizoctonia leguminicola* (blackpatch disease) growing on red clover leaves. The diseased forage, termed "slobber forage," can cause large production losses and the added cost of replacement forage (Aust 1974).

Toxic Compounds and Plant Resistance

Some of the secondary compounds discussed are associated with plant resistance to insect and disease attacks. Lignin formation is frequently a plant response to pathogen invasion (Bell 1981), and increased saponin concentration in alfalfa has been associated with increased insect and disease resistance (Hanson 1973). The results from breeding for low tannin in lespedeza provides a good example of such protection. A severe epiphytotic of *Rhizoctonia* spp. occurred in a nursery of plants developed for low-tannin concentrations, while the high-tannin lines (twice the tannin concentration) were not infested (Donnelly 1983). Tannin concentrations were negatively correlated (-0.43) with disease severity but accounted for only 18% of the variation. The remaining 82% of the variation was associated with other factors. Selecting for resistance to the fungus among the low-tannin lines resulted in a low-tannin and fungal-resistant cultivar (Donnelly 1983) with improved quantity. It is critical in forage-germplasm-enhancement programs that insect and disease resistance comes from direct gene action for the pathogen in question. Resistance from indirect causes, such as elevated concentrations of secondary compounds, may so adversely influence animal responses as to totally nullify the gains from selecting for either dry matter production or longevity of stands.

Future Research Needs

Two general areas warrant strong research programs:

1. Acute toxicity. Continued research is needed to characterize the secondary compounds in legume plants that cause acute animal toxicity. An understanding of the pathway of synthesis and biological activity of the compounds is important. Such information can be especially useful when incorporated into germplasm-enhancement programs. An understanding of gene action relative to specific compound synthesis is of significance. For example, if compound synthesis is under single-gene control, then breeding programs may be very effective in altering the occurrence of that compound in selected plants. Genetic engineering also offers potential in this area once appropriate technology is developed.

2. Subclinical toxicity. An area that appears not well explored is the adverse effects of plant compounds on animal performance when toxins are consumed at levels that do not cause clinical symptoms. Animal threshold levels from long-term studies need to be determined relative to plant concentrations, dosage consumed (daily and accumulated), and animal detoxification mechanisms (including both rumen microbial populations and shifts and animal physiological responses). Short-term high-dosage studies may give erroneous results.

Antiquality compounds that restrict the maximum genetic potential of an animal to perform relative to feed energy and nutrients consumed represent a serious threat to profitability.

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Discussion

Marten: Why is the quality of lespedeza so low?

Burns: There are two problems: firstly, high tannin concentration and, secondly, high fiber.

Rumbaugh: Toxicity of North American lupines is confused. One population may be high in alkaloid content, and a close neighbouring population, taxonomically considered the same, will have no alkaloids with no major environmental change.

Minson: Were toxicities on farm properties?

Rumbaugh: Yes, most problems occurred when animals were moved to unfamiliar areas.

Oestrogenic Activity in Forage Legumes

W.J. Collins and R.I. Cox[1]

Abstract

Several forage legumes contain oestrogenic compounds which can cause infertility and other reproductive disorders in grazing animals. Two groups of substances have been implicated: isoflavones, which are the principal phyto-oestrogens in clovers, and coumestans, which occur mainly in medics. In this paper, the current understanding of the oestrogenicity problem is outlined with particular reference to subterranean clover and the infertility syndrome known as "clover disease." Oestrogenic effects observed in sheep and cattle are described and the role of rumen metabolism in determining the oestrogenic activity of ingested phyto-oestrogens briefly reviewed. Factors influencing the levels of phyto-oestrogens in plants are also examined. Finally, the measures that have been employed to prevent the occurrence of clover disease or minimise its effects are discussed and some possible future approaches considered.

Introduction

Several pasture legumes that play a valuable role in the improvement of soil fertility and animal growth and production contain oestrogenically active compounds that can cause infertility and other reproductive disorders in animals that graze them. The main forage species involved are subterranean clover (Trifolium subterraneum L.), red clover (Trifolium pratense L.), lucerne (Medicago sativa L.), and some annual medics, such as barrel medic (Medicago truncatula Gaertn.). White clover (Trifolium repens L.), another valuable and widely used legume, is generally considered to be non-oestrogenic, although there have been occasional reports of oestrogenic effects of this clover in sheep and cattle. The oestrogenic substances are phenolic compounds of the isoflavonoid group (Wong 1973) (whose distribution is restricted essentially to the Leguminosae family); the principal phyto-oestrogens in subterranean clover and red clover are isoflavones, whereas the medics and the white clover contain coumestans.

The first indication of the potential deleterious influence of phyto-oestrogens on animal production came in the early 1940's in Western Australia when Bennetts et al. (1946) suggested that the serious reproduction disorders observed in sheep grazing subterranean-clover dominant pastures were probably associated with oestrogenic activity in the clover. Then followed a period of intensive scientific investigation which continued over the ensuing three decades before tapering off in the mid-1970's. The findings from this research effort have contributed greatly to the understanding of the oestrogenicity problem and the development of measures for its control.

The literature on oestrogenic activity in pasture legumes has been reviewed regularly (see Pope 1954, Moule et al. 1963, Bickoff 1968, Rossiter 1970, Braden and McDonald 1970, Barden and Shutt 1970, Cox and Braden 1974, Lightfoot 1974, Shutt 1976, Cox 1978, McDonald 1981, Hegarty 1982) and will not be attempted here. Our purpose in this paper is to outline the current understanding of the phyto-oestrogenicity problem and the measures available for its control. Reference will be made to some more recent research developments and to areas where we believe further research is required. Much of the paper is based on research relating to subterranean clover, a species which, in the past, has been responsible for severe oestrogenicity problems in sheep.

Oestrogenic Effects in Grazing Animals

Sheep

Two infertility syndromes have been recognized in sheep grazing oestrogenic subterranean clover and red clover pastures. The first, and more severe, occurs where sheep have been grazing oestrogenic pastures for several years and is characterized by a progressive decline in ewe fertility. Other features of this syndrome, which became known as "clover disease," include maternal dystokia, uterine prolapse, increased death rate of ewes, post-natal mortality of lambs, and lactation in both virgin and non-pregnant ewes and in wethers. Problems of urinary obstructions and enlargement of the bulbo-urethral glands (false bladder) in wethers have also been associated with clover disease. The fertility of rams grazing oestrogenic pastures is apparently not affected. Pathologically the syndrome in ewes is characterised by cystic glandular hyperplasia in the cervix and uterus, together with several other morphological and histochemical changes (Adams 1976a).

Severe clover disease was prevalent in the decade 1940 to 1950 in Western Australia. Lamb marking percentages in affected areas fell to 30% (and in some cases as low as 10%) while ewe mortality rates of 20% to 30% were not uncommon. Although the more extreme symptoms are seen only rarely today, clover disease remains a problem of some economic significance. Lightfoot, in 1974, indicated that reproductive wastage due to clover disease was still widespread in Australia but that it occurred as a comparatively uncomplicated infertility. This is still an accurate assessment of the problem.

The main cause of infertility is impaired transport of spermatozoa through the cervix, which is associated with the production of abnormal cervical mucus. Because infertility persists for several years after ewes are removed from oestrogenic pastures, it is commonly referred to as "permanent infertility."

The second syndrome, known as "temporary infertility," occurs when ewes graze highly oestrogenic pasture at the time of mating (Morley et

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al. 1964, Clark 1965). Although this can cause a substantial reduction in lambing percentage, the infertility does not persist if the sheep are removed from the oestrogenic pasture. The available evidence suggests that the reduction in fertility is due to a decrease in both ovulation and fertilization rate and a reduction in the rate of transport of ova through the oviducts.

Reproductive disorders in ewes attributed to the ingestion of coumestans include delayed oestrus and a reduction in ovulation rate. Both oestrus and ovulation are inhibited where pastures contain very large amounts of coumestans (e.g., 1000 ppm), but where levels are lower (e.g., 400 ppm or lower), only ovulation rate is affected. Coumestrol levels as low as 25 ppm in the diet have been shown to significantly depress ovulation rate (Smith et al. 1979). The effects of coumestans on fertility are usually less severe than those caused by clover disease, and recovery is rapid following removal from the oestrogenic pasture. In this latter respect the problem is akin to the temporary infertility described above. There have been no reports of permanent effects of coumestans on fertility.

Cattle

Despite a number of reports of hyper-oestrogenic syndromes (with infertility and irregular oestrous cycles as key features) in cattle receiving oestrogenic forages, the extent to which phyto-oestrogens cause deleterious effects in cattle remains unclear. For subterranean clover, the indications are that while some reproductive losses may occur, in contrast to the problems in sheep, these are likely to be of limited economic significance. There have been no reports of major problems in Western Australia.

Physiological Changes and Bioassays

There have been several investigations of endocrine and cellular changes occurring in animals following intake of phyto-oestrogens. Some of the responses observed have been used to develop bioassays.

Responses to Isoflavones in the Ewe

The increase in uterine weight in ovariectomised ewes associated with oestrogenic stimulus has been widely used in bioassays (Davies and Bennett 1962, Bennett and Dudzinski 1967). However, a more sensitive and precise indication of oestrogenic stimulation is the change in RNA:DNA ratio in uterine tissue (Little and Lambourne 1976).

The cervix of ewes affected with clover disease shows differentiation changes towards a more uterine-like appearance histologically, and has an altered responsiveness to oestrogen (Lightfoot and Adams 1979, Adams 1981). The change in consistency of cervical mucus in ovariectomised ewes following exposure to oestrogen has been the basis of useful bioassays (Turnbull et al. 1967, Lindsay and Francis 1968). However, responses are not quantitatively reliable if animals are exposed to oestrogen for more than a few days, because of the development of a refractory phase (Adams 1977).

Masculinisation of external genitalia, which has been observed in ewes following prolonged grazing of oestrogenic pastures, may provide a useful test to assess cumulative exposure to phyto-oestrogens (Adams 1979). There is a need for the development of improved methods of monitoring grazing animal responses to phyto-oestrogens, particularly cumulative responses. These would be applicable in pastures of potential hazard or where efforts are being made to reduce oestrogenicity.

Ewes which have developed infertility from phyto-oestrogen intake show changes in both basal luteinizing hormone (LH) levels and LH responses to administered oestradiol (Findlay et al. 1973, Rodgers et al. 1980, Chamley et al. 1981, Adams and Martin 1983). These effects reflect alterations in the sensitivity of hypothalamus and pituitary feedback to oestradiol.

The measurement of phyto-oestrogens in blood has been related to oestrogen intake in some experiments (e.g., Lindner 1967, Shutt et al. 1969). Such an approach may have wider application through the use of newer analytical techniques. The use of competitive binding assays with oestradiol reactive uterine cytosols has been shown to give a quantitative biochemical measure with individual phyto-oestrogens and can be used to detect unknown oestrogens (Shutt and Cox 1972, Hesse et al. 1981, Wagner and Jackson 1983).

Responses in Wethers to Isoflavones

Increase in teat length in whethers is a sensitive and rapid response to pasture oestrogens (Braden et al. 1964). Its main limitation as a bioassay is that it is too sensitive, and a response ceiling is reached at a relatively low level of phyto-oestrogen. Changes have been found to occur in the enzymes in the teats of wethers following exposure to oestrogens, and these may be used in a bioassay system (Smithard et al. 1975).

To assess the effect of higher levels of phyto-oestrogen as a cumulative response over several weeks or months, enlargement of the bulbo-urethral gland in young wethers offers a useful index (Obst 1971).

Phyto-Oestrogens in Forage Legumes

Isoflavones

The main oestrogenic isoflavones isolated from *Trifolium* species are formononetin, genistein, biochanin A and daidzein; in some cases low concentrations of pratensein have also been recorded. The first three are often found in high concentrations in subterranean clover and red clover, with combined levels in the leaves of up to 5% on a dry matter basis. Although only weakly oestrogenic (about 10^{-5} to 10^{-6} times as active as oestradiol), they have a significant biological effect in animals because of the large quantities ingested (Braden et al. 1967). Isoflavones occur in the plant mainly as glycosides which are rapidly hydrolyzed by glycosidases when the leaf cell structure is ruptured.

Coumestans

Coumestrol and 4'-O-methyl coumestrol, together with several other coumestans as minor constituents, have been isolated from medics and some clovers. Compared with the isoflavones, coumestans are much more oestrogenic (coumestrol is about 10^{-3} times as active as oestradiol), but their levels in plants are much lower. In many species, levels are normally only a few ppm and are often considered to be of little significance oestrogenically. However, high levels (>1000 ppm), sufficient to cause marked oestrogenicity problems, have been reported in lucerne, white clover, and some annual medics following infection with fungal foliar pathogens.

Metabolism of Phyto-oestrogens in Ruminants

It is now well established that the relative importance of individual isoflavones in the oestrogenicity problem in sheep is largely determined by their metabolism in the rumen (for reviews see Braden and McDonald 1970, Cox 1978, Peinado Lucena et al. 1982). Formononetin is believed to be the most important isoflavone in subterranean clover and red clover because, although it has little oestrogenic activity itself, in the rumen it is converted mainly to equol, with some 4'-O-methylequol (Cox and Braden 1974, Nottle and Beck 1974) and small amounts of daidzein and O-desmethyl angolensin, all of which are oestrogenically active. Equol is probably the main oestrogen responsible for clover disease. The 5-hydroxy-isoflavones, genistein and biochanin A, which are both oestrogenic when given parenterally, are largely catabolised by rumen micro-organisms to p-ethylphenol and other simple phenols which are oestrogenically inactive (Braden et al. 1967, Batterham et al. 1971). However, the microbial inactivation pathway does not develop fully until animals have been grazing for several days on forage rich in these isoflavones, and animals may show oestrogenic responses until this time.

There is evidence to suggest that the metabolism of isoflavones by cattle follows the same pathway as that observed in sheep. However, the rate of metabolism and the rate of conjugation of the metabolites in the liver, which renders them oestrogenically inactive, may be faster in cattle (Braden and Shutt 1970). This could provide a possible explanation for the apparent lower susceptibility of cattle to the oestrogenic effects of clover pastures.

Little is known about the metabolism of coumestans in the rumen, except that 4'-O-methyl coumestrol is demethylated to coumestrol (Shutt et al. 1969). The finding that oestrogenic response in sheep (based on the cervical mucus bioassay) decreased with increasing exposure to coumestans (Kelly and Lindsay 1975) raised the question as to whether sheep could inactivate coumestans as they do genistein and biochanin A. But, after further research Kelly and Lindsay (1978) suggested that the most likely explanation for the decreased response was that sheep became insensitive to coumestans. This is consistent with Adams' (1977) explanation for the decreased cervical mucus response in ovariectomised ewes following prolonged exposure to oestrogenic isoflavones.

Phyto-oestrogens and their metabolites are absorbed, largely from the rumen, into the bloodstream. Following conjugation in the liver with glucosiduronic acid, they circulate in the plasma mainly in the form of glucosiduronates, which are presumably oestrogenically inactive. (It would thus appear that any aberration in liver function could markedly influence the oestrogenic activity of ingested clover.) Cox (1978) has indicated that less than 1% of isoflavones and their metabolites are present in the biologically active unconjugated form and small amounts appear to be present as the sulfo-conjugates, which are of significance because they can probably be converted _in vivo_ to the active free form. For coumestrol, relatively high proportions (20% to 50%) are present as unconjugated and sulfo-conjugated forms (Cox 1978, Kelly and Lindsay 1978).

Factors Affecting Phyto-oestrogen Levels in Legumes

Subterranean Clover

A feature of clover disease in southern Australia is its variability in both incidence and severity. There have been numerous reports of differences in severity between Western Australia and other Australian States as well as between regions within Western Australia. Several factors could contribute to this variability. In addition to differences in oestrogenic activity arising from the use of different cultivars, variation in botanical composition of the pastures, selective grazing by animals, and differences in sensitivity of animals to oestrogens have all been suggested as factors contributing to the variations in incidence and severity of clover disease. Also, a number of factors related to the environment, nutrition, and management under which subterranean clover is grown have been implicated. Studies of their effects on phyto-oestrogen levels have been made in an attempt to better explain the incidence and severity of clover disease (Rossiter 1970).

Nutrients. Moderately severe deficiencies of phosphorus (P), sulphur (S), and nitrogen have been shown to greatly increase isoflavone levels (almost double for formononetin) in subterranean clover; while potassium (K), copper, and zinc deficiencies had negligible effects. Similar findings for P and K have been reported for red clover (Butler et al. 1967). Confirmation that P deficiency increases the oestrogenic potency of subterranean clover was obtained using the cervical mucus bioassay in sheep (Neil and Marshall 1970).

Plant Maturity. There is evidence that isoflavone levels in subterranean clover decrease with increasing age of plants, although this trend is apparently strongly strain-dependent (Rossiter and Beck 1967). It might be expected, therefore, that oestrogenic activity would also decline with increasing plant age, particularly considering that the proportion of leaf in clover herbage, which is the most oestrogenically active component, also declines with plant growth and development. But evidence on this point is equivocal. Rossiter and Beck (1967) suggested that the absence of a decline in oestrogenic activity with time might be because the lower isoflavone levels are offset by a higher

intake of clover leaf or because compounds other than the known isoflavones influence the level of oestrogenicity.

Mature subterranean clover which has been allowed to dry naturally in the field appears to have relatively low oestrogenicity, and breeding animals grazing dry subterranean clover pastures over the summer period are likely to be safe from oestrogenic effects. This is in contrast to the situation with the perennial legume red clover where oestrogenicity may be a problem throughout the year (Kelly et al. 1979).

Both freshly cut, green, subterranean clover which has been rapidly dried artificially and good quality field-cured subterranean clover hay may retain a high degree of oestrogenic activity (Davies and Dudzinski 1965). However, haymaking, presumably under less ideal conditions, can result in a diminution of oestrogenic activity in subterranean clover (Davies and Dudzinski 1965), as it does in red clover (Kelly et al. 1979).

Other Factors. The effects of temperature, light, waterlogging, moisture stress (R.C. Rossiter, personal communication), and defoliation on isoflavone levels in subterranean clover have also been examined. At extreme levels, they have all been found to influence isoflavone concentrations in the leaves. However, under most field conditions it appears unlikely that these factors would contribute significantly to the incidence or severity of clover disease.

Medics and White Clover

Infection with foliar fungal pathogens appears to be the most important factor which can cause rapid and marked increases in coumestan concentrations in these species. Increases have been shown to be directly related to the degree of plant infection and may be as high as 100-fold or more. Low superphosphate levels increased coumestrol content two-fold in the dry burr and stem of the annual *Medicago littoralis* cv. Harbinger (Marshall and Parkin 1970).

In the absence of disease, coumestrol content varies markedly with stage of growth in annual medic species (Francis and Millington 1965) but not in lucerne (Loper and Hanson 1964). The level of coumestrol in the annual medics was found to be low until the beginning of flowering, but thereafter increased until after the plants were mature and field dry, with maximum concentrations occurring in the dry stems and pods. Thus, in contrast with subterranean clover, where only the green herbage is oestrogenically active, in the annual medics it is the mature and dry pasture which is likely to provide the greatest risk for breeding animals.

Methods for the Control of Clover Disease

Both agronomic and animal husbandry measures have been recommended to minimise the effects of clover disease or to prevent its development and these have been discussed in detail most recently by Marshall (1973) and Lightfoot 1974).

Plant-directed Methods

The underlying aim of these procedures is to reduce the quantity of the phyto-oestrogens ingested by the animal and thus prevent clover disease or at least restrict its development.

Reduction in Clover Content of the Pasture. One of the early recommendations for the prevention of clover disease was to introduce or encourage species other than subterranean clover in the pasture. The field observation (R.C. Rossiter, personal communication) that cultivars high in formononetin were relatively unpalatable to sheep suggested that increasing the proportion of non-oestrogenic species in the pasture would encourage the selection of a low-oestrogen diet.

A question of practical significance is whether there is a level of oestrogenic clover content below which a pasture can be considered "safe." As Rossiter (1970) has indicated, by the late 1950's it was commonly believed that clover disease was only associated with highly clover dominant pastures and that pastures containing less than 50% clover were probably safe. However, increased stocking rates since that time have reduced the opportunity for selective grazing, and it has been suggested that even pastures with only 20% to 30% oestrogenic clover may not be safe in the longer term (Marshall 1973, Lightfoot 1974).

Adequate Mineral Nutrition of the Pasture. The main consideration is that pastures are adequately supplied with P and S and that clover plants are adequately nodulated. Severe P deficiency (with plants showing marked symptoms) will increase formononetin level, but milder deficiencies can play an indirect role in increasing pasture oestrogenicity by increasing the proportion of clover in pasture (Rossiter 1964).

Use of Cultivars with Low Oestrogenic Activity. There is considerable genetic variability in oestrogenic activity in subterranean clover, and it is fortuitous that many of the cultivars that were first used were highly potent. The main effort to control clover disease has been through the development of low oestrogenic cultivars. Breeding for low oestrogenicity commenced in Western Australia in the 1960's following the identification of formononetin as the key isoflavone and the development of a thin-layer chromatographic technique (Francis and Millington 1965) which enabled the rapid determination of isoflavone levels in plants. Replacements for the oestrogenic cultivars, Dwalganup, Yarloop, and Geraldton have already been developed (cvv. Northam, Trikkala, and Nungarin, respectively), and further low formononetin releases are imminent. Low formononetin continues to be a primary selection criterion in the National Subterranean Clover Improvement Programme (see W.J. Collins and J.S. Gladstones, "Breeding to Improve Subterranean Clover in Australia," later in this proceedings).

The question of what is a safe level of formononetin in subterranean clover cultivars cannot be resolved precisely, since the concentration of formononetin in the plant can, at best, be only a rough guide to

animal intake of formononetin cumulated over time. Nevertheless, from field observations on ewe fertility, cultivars with a formononetin content of 0.3% or less (on a leaf dry weight basis) have appeared to be safe and on this basis a maximum level of 0.2% has been used as a guide to selection in the breeding programme. But even lower levels of phyto-oestrogen may be desirable. Adams (1976b) found slightly abnormal cervical mucus in ewes that had grazed the Northam cultivar (0.1% formononetin) for four years and suggested that the possibility this might be reflected in permanent subclinical infertility needed further investigation. It is also interesting to note that in lucerne, Smith et al. (1979) found that coumestrol levels as low as 25 ppm in the diet, fed as pellets, depressed ovulation rate in sheep. This suggested that the effective level of coumestan was much lower than previously accepted. There is no difficulty in achieving levels of less than 0.1% formononetin in cultivars of subterranean clover since such levels are common in the existing collection of overseas and naturalized strains.

The effectiveness of low oestrogenic cultivars in reducing clover disease will depend on their ability to replace oestrogenic cultivars in existing pastures. Where oestrogenic cultivars are well adapted and have built up large reserves of seed in the soil, replacement may be facilitated by measures aimed at reducing the seed bank, such as successive years of cropping, prior to oversowing with new cultivars. But, it is also essential that the new cultivars are successful in mixtures with the cultivars they are designed to replace. There is field evidence that in some cases this occurs, e.g., Trikkala and Daliak can become highly dominant in mixtures with the oestrogenic cultivars Yarloop and Dwalganup, respectively, although the underlying reasons are, as yet, not fully understood. Competitive advantage is only one of several key factors influencing the success of subterranean clover strains in mixtures (Rossiter and Palmer 1981). Other parameters such as over-summer seed survival, hard-seededness, and seedling survival can also be important determinants of success (R.C. Rossiter, personal communication).

Animal-Directed Methods

There is no known cure for permanent infertility. Thus, as Lightfoot (1974) has indicated, where clover disease is already severe and lambing percentages are so low that it becomes unprofitable to continue breeding, at least with stock bred on the property, consideration should be given to alternative enterprises. Three possibilities have been suggested:

1. Graze sheep for wool production only and gradually change to an all wether flock where the effects of clover disease are likely to be less severe

2. Maintain a breeding programme by regularly purchasing replacement ewes from non-oestrogenic clover areas

3. Change from sheep to cattle grazing because the effects of prolonged intake of phyto-oestrogens appears to be much less severe in cattle.

Fortunately, extreme forms of clover disease necessitating consideration of these options has been extremely rare for many years.

Where some degree of permanent depression in infertility has already occurred and/or animals are likely to be at risk from oestrogenic pastures, the following management practices have been recommended.

Grazing Management. Because prolonged exposure to phyto-oestrogens results in cumulative and permanent infertility, the total breeding productivity of young ewes will be more affected than that of old ewes. Thus, to minimise the overall effects of clover disease, grazing should be strategically allocated amongst various classes of sheep so that groups likely to be most affected (ewe weaners and young ewes) graze the least oestrogenic pastures, while the least easily affected (old ewes and wethers) graze the most potent pastures. This strategy, of course, rests on the assumption that not all pastures on a property will be equally oestrogenic. Mating on oestrogenic pastures should be avoided because of the risk of temporary infertility.

Joining Husbandry. Because infertility in ewes affected with clover disease is associated with poor sperm transport through the genital tract, it has been suggested that fertility could be improve by increasing the number of services per oestrous ewe. Lightfoot (1974) indicated there was evidence that increasing the ram/ewe ratio during joining resulted in higher fertilization rates, although there was insufficient information to make a specific recommendation.

It has also been suggested that fertility could be improved by prolonging the joining period. However, this strategy is limited because of the management problems associated with an extended lambing period.

Lambing Husbandry. Lightfoot (1974) has suggested that through close vigilance of lambing flocks, particularly young ewes, assistance can be given during lambing which will minimise losses from dystokia.

Possible Future Control Through Animal Treatment

Although, at the present time, reducing the intake of phyto-oestrogens by the animal appears to be the most effective means of preventing clover disease, a number of ways have been suggested in which prevention could operate through treatment of the animal (for review, see Cox 1978).

Hormonal Treatment. Hormonal treatment of wethers through the injection of androgen to counter the effects of ingested oestrogen, has shown some promise. However, hormonal treatment of the ewe, without disturbance of the oestrous cycle, has not proved satisfactory (Cox 1978).

Immunization. Immunization of the ewe against phyto-oestrogens has been investigated as a method of neutralizing their activity. Phyto-oestrogen-protein conjugates have been effective immunogens for raising specific antisera. Partial blocking of phyto-oestrogen action has been observed, with ewes immunized against equol analogues showing marked

protection against equol infused over a period of three days (Cox et al. 1983). But, in tests with grazing animals, protection was less effective, possibly due to the prolonged intake of oestrogen or to effects of other phyto-oestrogens (summarized in Cox 1978). A clearer understanding of biochemical changes and the dynamics of metabolism in the immunized animal is needed to make further progress with this approach.

Another immunization approach under test is directed at countering the effects of coumestans. A main effect of coumestans is to decrease the ovulation rate of ewes (Smith et al. 1979) whereas immunization against steroids is known to increase ovulation rate (Cox et al. 1982). Steroid immunization has been shown to offset, at least in part, the deleterious effects of coumestrol on ovulation rate (Smith et al. 1982). This approach may be of practical use.

Alteration of the Metabolism of Phyto-oestrogens in the Animal. Altering metabolic conversions has the potential to reduce the biological effects of phyto-oestrogens, particularly since it has already been established that biochanin A and genistein are normally converted to inactive products in the rumen. Can analogous conversions be stimulated for formononetin? It is noteworthy that the main metabolites of formononetin result from hydrogenation and demethylation whereas the 5-hydroxy-isoflavone biochanin A is demethylated to genistein and catabolism proceeds through to ring cleavage and formation of inactive simple phenols.

The major metabolite of formononetin in the rumen is equol. But other metabolites have been found including 4'-O-methylequol, which is less oestrogenic than equol and is a product of formononetin metabolism via an alternative route involving reduction without demethylation. Although the broad framework of metabolic conversions of phyto-oestrogens in animals has been established, more detailed research is still required in this area. An understanding of the factors influencing the metabolism of formononetin through various pathways could be of significance in minimising clover disease.

The role of ruminal microbes in the metabolism of toxic constituents in plants is well known (Allison 1968). An interesting question arises as to whether ruminal microbes exist that are capable of detoxifying equol or selectively converting formononetin to less active metabolites, but which are not present in Australian animals. In this context, recent work with mimosine, a toxic amino acid found in the legume Leucaena leucocephala, is of interest. Jones (1981) suggested that rumen micro-organisms capable of detoxifying 3-hydroxy-4(1H)-pyridone (DHP) (the goitrogenic degradation product of mimosine in the rumen) were present in goats in Hawaii but did not occur in Australia. Subsequently, Jones and Lowry (1984) reported that metabolism of DHP in Australian animals was promoted by inoculation with rumen microbes collected from animals capable of metabolising DHP. This would seem to be a useful area for investigation in relation to diverting the metabolism of oestrogenic isoflavones in ruminants to inactive products, particularly in view of the precedent that genistein is inactivated by rumen micro-organisms.

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Discussion

Barry: There is some confusion on whether the effect of formononetin is accumulative or whether a threshold level exists.

Collins: Western Australian view is that the effect of formononetin is accumulative. Current opinion is that there is not a threshold level.

Marten: Is there any evidence that phyto-oestrogens have a positive effect on weight gains?

Collins: Yes, but I cannot give you the details.

Barry: In New Zealand, the feeding value of legumes is greater than grasses; therefore red clover would be recommended as a feed.

Marten: Analogue of oestrogens may promote growth.

Barry: In New Zealand, we have never isolated oestrogen effects vs. higher protein at the duodenum.

Runge: Are there any disease or pest interactions on formononetin?

Collins: Unpublished work in Victoria looked at the fungal foliar pattern on a range of cultivars. The results as I recall were equivocal.

Lancashire: An Australian low formononetin selection stated to be 0.1% was used in New Zealand and never got below 0.3%. Is formononetin expression dependent on location?

Collins: It is possible that there is a location effect. The figures are from a modified thin-layer chromatography technique that is only semiquantitative so that only a range of results can be stated with confidence.

Sheath: In North Island New Zealand, hill country formononetin ranged from 0.1% to 2% depending on genotype. There was little change in concentration from winter to the end of spring. When old ewes from properties with the most subterranean clover were slaughtered, there were no signs of permanent fertility.

Germplasm Sources for Genetic Improvement of Forage Legumes in Australia and New Zealand

R.A. Bray[1]

Abstract

The extent of genetic resources of forage legumes is assessed in terms of the available cultivars and material held in collections of various species and genera. Summaries are given of collections held in Brisbane, Townsville, Adelaide, Perth, and Palmerston North. The relatively undeveloped state of tropical forage legumes is emphasized. Some of the major requirements for forage legume genetic resources in the future include more support for maintenance and description of existing collections, further collecting where needed, research on methods of screening, seed storage, and releasing variation.

Introduction

The nature of the genetic resources of forage legumes as a whole has been well covered in a recent book (McIvor and Bray 1983), incorporating chapters on tropical legumes (by R.J. Williams) and on temperate legumes (by M.J. Mathison). Other chapters dealing with the collection, maintenance, description, and utilisation of these resources provide a comprehensive overview of the subject.

In this paper I will take a more restricted view of germplasm resources. I will attempt to summarise what material is available (as commercial cultivars or in collections) and to try and decide whether or not this forms an adequate resource. I will also discuss some of the obvious research needs in this field.

The Extent of the Resources

Resources in Cultivars

Since the climates of Australia and New Zealand cover a wide range of temperature and moisture regimes, almost all legume species, other than those suited to cold temperate areas, must be considered. Mathison (1983), in his broad overview of forage legumes for grazed pasture, cut fodder, and harvested seed crop, lists some 67 species (including 14 *Medicago* and 14 *Trifolium*) used in temperate agriculture. Those species used in Australia and New Zealand are listed in table 1, together with some details on the origin of the species, and the number of registered cultivars. (The number of registered cultivars is probably an underestimate of the number actually in use, since, especially in *M. sativa*, many recently imported aphid-resistant cultivars are not officially registered.)

In contrast, only 30 cultivars in 17 species are available in tropical legumes in Australia (table 2). This of course reflects the historical agricultural development of the country (and indeed the world) in that the more intensively developed temperate areas have been able to call upon the "traditional" Asian and European genera in their farming systems. The more recent development, and smaller areas involved, of the tropics and subtropics has not yet resulted in a large number of well-adapted forage legume cultivars.

All these cultivars (both temperate and tropical) represent a valuable source of germplasm in themselves. Not only are they well adapted to their target environments, but they also contain many desirable genes and gene combinations that are not immediately apparent. From a survey of crop breeders in the United States, Duvick (1983) established that, almost without exception, when new diseases arose, it had been possible to find suitable resistances within existing cultivars or well-adapted breeding populations. It had not been necessary to go to the wild relatives of commercial cultivars to find resistant genes, even though this is one of the main reasons for interest in such material.

Even considering the large number of overseas cultivars of some species, it is unlikely that this fortunate situation exists for forage plants, since far fewer cultivars have been developed (by far fewer workers!) over a much shorter period than with crops. It is certainly not true for tropical forages where development is only just beginning. We may be approaching this position in a species such as lucerne (*M. sativa*) where extensive collections exist both in this country and overseas and broad-based germplasm pools have been established.

Resources in Collections

Most people working on legumes have their own collections (including breeding lines), and it is not possible to document these accurately. However, in Australia, the major collections are held by CSIRO and the various State Departments of Agriculture. In New Zealand, the Grasslands Division of DSIR holds the major collections.

In Australia, over the last few years there has been considerable interest in formalising the genetic resources of the country, and a network of Genetic Resource Centres has been established, at least in principle. It is intended that these centres be responsible for forage legumes: CSIRO Division of Tropical Crops and Pastures (Brisbane and Townsville) would deal with tropical legumes; the South Australian Department of Agriculture (Adelaide) would manage *Medicago*, and the West Australian Department of Agriculture (Perth) would maintain *Trifolium* and other temperate legumes.

The collections to be kept in these centres (or at present being held) are of very different compositions, as might be expected from the previous discussion on temperate and tropical cultivars. The "tropical" collection contains over 175 genera (and a total of over 13,000 accessions), but 114 of these genera have less than 10 accessions. Twenty-seven genera have over 100 accessions, including four with

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Table 1 - Species of temperate legumes used in Australia and New Zealand

Genus	Species	Commom name	Origin of[1] species	Approx. No.[2] of cultivars
Astragalus	hamosus	milk vetch	E. Med., W. Asia, Cauc	1
Lespedeza	striata	Japanese lespedeza	E. Asia	1
Vicia	sativa	common vetch	Med., Eu., S.W. Asia	4
	villosa	woolly pod vetch	Med., S.W. Asia	1
	benghalensis	purple vetch	S. Eu.	1
Medicago	littoralis	strand medic	Med., N.W. Asia	1
	polymorpha	burr medic	Med., Eurasia	2
	rugosa	gama medic	Med.	3
	sativa	lucerne	N.W. Asia	15+
	scutellata	sanil medic	Med.	3
	tornata	disc medic	Med.	3
	truncatula	barrel medic	Med.	10
Trifolium	ambiguum	caucasian clover	Cauc., N.W. Asia	4
	cherleri	cupped clover	S.W. Asia, Med.	3
	fragiferum	strawberry clover	Eurasia, N. Afr.	3
	hirtum	rose clover	S.W. Asia, Med.	4
	pratense	red clover	N. temperate	4
	repens	white clover	Temp. Eurasia, E. Med.	7
	semipilosum	Kenya white clover	E. Afr.	1
	subterraneum	subterranean clover	Med.	24
Lotus	uliginosus	greater lotus	Eu., N. Afr.	1
Ornithopus	compressus	yellow serradella	Med.	1
Onobrychis	viciifolia	sainfoin	W. Asia	1
Lupinus	albus	white lupin	Eu., Balkans, E. Med.	3
	angustifolius	blue lupin	Med.	12

[1]Abbreviations are obvious, except Cauc. = Caucasus.

[2]Mainly from Register of Australian Herbage Plant Cultivars.

Table 2 - Species of tropical legumes used in Australia

Genus	Species	Common name	Origin of species	No. of cultivars
Aeschynomene	falcata	joint vetch	S. America	1
Centrosema	pubescens	centro	Tropical Am.	1
Desmodium	heterophyllum	hetero	Tropical Am.	1
	intortum	desmodium	Central Am.	1
	uncinatum	desmodium	Brazil	1
Lablab	purpureus	lablab bean	E. Africa	2
Macrotyloma	axillare		E. Africa	1
	uniflorum		E. Africa	1
Neonotonia	wightii	glycine	E. Africa	4
Lotononis	bainesii	lotononis	S. Africa.	1
Macroptilium	atropurpureum	siratro	Mexico	1
	lathyroides	phasey bean	Tropical Am.	1
Stylosanthes	guianensis	stylo	Tropical Am.	6
	hamata	Caribbean stylo	Venezuela	1
	humilis	Townsville stylo	Tropical Am.	3
	scabra	shrubby stylo	Brazil	2
Leucaena	leucocephala	leucaena	Mexico	2

over 1000. The number of accessions held in 29 major genera are listed in table 3.

Details of the South Australian and West Australian collections are given in table 4. The contrast with the tropical collection is immediately obvious: although the total numbers involved at each centre are of the same order of magnitude, far fewer species, each generally represented by a reasonable number of accessions, are involved for the temperate legumes.

Although this summary does not give an exact assessment of the resources either *in toto* or at each site (e.g., many of the 1172 *Trifolium* accessions in Brisbane are probably duplicated in Perth), it is a reasonably accurate list of the resources that are potentially available for future work.

The DSIR Grasslands Division legume collection totals about 12,450 accessions (M.B. Forde, personal communication). However, about half of these are breeding lines used by individual breeders and not generally available to anyone else. It is not usual for this sort of material to be included with introductions, and it is therefore difficult to compare these figures with those from other institutions. The numbers given in table 5 include the breeding lines mentioned above, cultivars, wild introductions from outside New Zealand, and New Zealand collections of permanent pasture species.

Future Uses of Collections

Although the numbers in the above collections seem, at first glance, to be large, the one major question that must be asked is: Do they contain what we need for the future? This question must surely be of vital importance to each and every collection. In the paragraphs below I will consider this subject only from the point of view of cultivar development. This is of course not the only (or even the major) use of these collections. Different arguments may be relevant for genetic conservation *per se*, or for the use of a collection for botanical or population biology studies.

What characters will be needed in future cultivars? Is it in fact possible to anticipate what these characters might be? One thing that is certain is that we will be challenged by new pests and diseases. The quarantine systems of Australia and New Zealand, although undoubtedly effective in delaying the advent of overseas pestilences, are unlikely to prevent their entry forever. Two

Table 3 - The extent of collections held by CSIRO Division of Tropical Crops and Pastures--major genera[1]

Genus	No. of accessions	Genus	No. of accessions
Aeschynomene[2]	365	Lotus	174
Alysicarpus[2]	108	Macroptilium[2]	597
Arachis[2]	29	Neonotonia[2]	253
Cajanus	176	Phaseolus	460
Cassia[2]	200	Psophocarpus	109
Centrosema[2]	1160	Rhynchosia[2]	216
Clitoria[2]	134	Sesbania[2]	138
Crotalaria[2]	289	Sylosanthes[2]	1529
Desmanthus[2]	291	Tephrosia[2]	161
Desmodium[2]	844	Teramnus	157
Galactia	186	Trifolium	1172
Glycine	90	Vicia	111
Indigofera[2]	365	Vigna	1052
Leucaena[2]	690	Zornia	142
Lotononis	100		

[1]Details provided by R.J. Williams.

[2]Genus with accessions well characterised or in process of description.

examples that come readily to mind are the appearance in the mid-1970's of the spotted alfalfa aphid, long known in the United States, and of Siratro rust (known from Florida and Central America). How these organisms arrived is of no concern. In the event, there was little resistant germplasm (for the aphid) available in Australasia, but it was quickly introduced; its speedy incorporation into testing and breeding programs necessitated a major relaxation of the quarantine procedures. In the case of Siratro rust, with no other commercial cultivars available, collections made in Mexico (the centre of origin of Macroptilium) contained many accessions that were rust resistant.

For species that are widely grown (and researched?) overseas, it might be expected that diseases (and resistances) important there will eventually be relevant to Australasia. For species grown extensively mainly in Australia (e.g., subterranean clover), new diseases may originate within our own system, and we will then need to be able to screen existing collections for suitable resistances.

One other major area of interest in new cultivars will be the exploitation of new environments. These environments will almost certainly be more unfavourable than those in which the current cultivars are grown, e.g., cooler, drier, less fertile, more saline, etc. The pressure is always on to extend the range of currently adapted species. The genes (or gene complexes) needed to provide such adaptations might be able to be located through a knowledge of environments where collections were made. The fact that they are likely to be complexes of co-adapted genes is a strong argument for integral maintenance of accessions, rather than the formation of germplasm pools.

The collections will also need to provide specific characters for selection and breeding programs (e.g., the single-gene characters in lupins). Although such desirable characters will not always be simply inherited, they will often be needed in breeding programs, whereas many of the more complex objectives (such as "adaptation") may be mainly achieved through introduction and testing programs.

Whatever direction these future demands might take, it is certain that they will occur. Are the necessary characters contained in our collections? This query immediately raises two further questions: (1) Do we know what is contained in our collections, and (2) What seed is available from these collections?

Whether or not a collection (i.e., its member accessions) is fully characterised depends on many factors. Perhaps the most important one is whether an accession has been acquired from another institution (or person) or collected in the wild. Australia's forage legumes have been 70% acquired by collection, and therefore require description before being of any use. On the other hand, New Zealand collections have all been acquired from other institutions and presumably need less preliminary descriptive work.

When attempting to characterise any accession it is obviously much easier to screen for a single, specific character (e.g., resistance to a particular disease, or flowering time) than for some complex trait, such as yield or "adaptation." However, even with the recent trend to using standard descriptor sheets, few collections are adequately described. This is particularly true of "untamed" species, and therefore of tropical collections. This is partly due to the nature of the primary plant introduction process, which is constantly providing a stream of plants which should be quarantined and examined for "general adaptation." However, of the 29 genera in table 3, 17 have been described in some detail (or are currently being described).

Given that we can determine the characteristics of a particular desirable accession, is seed available? Just because a number exists in a list is no guarantee that viable seed is on hand. As an example, a recent request from New Zealand for Trifolium spp. for the hill country in the South Island was met with a list of about 100 suggested accessions for trial. Of these, only four are still available (R. Reid, personal communication). It is unfortunate that once material is in a "gene bank,"

Table 4 - Details of major collections of temperate legumes in Australia

Location	Genus	Species	No. of accessions
Adelaide[1]	Medicago	annuals	
		aculeata	369
		arabica	34
		blancheana	57
		constricta	122
		intertexta	278
		littoralis	770
		minima	52
		murex	138
		orbicularis	812
		polymorpha	1036
		rigidula	647
		rotata	88
		rugosa	103
		scutellata	150
		tornata	365
		truncatula	2157
		truncatula x littoralis	176
		turbinata	129
		other spp.	111
		biennial, lupulina	69
		perennial, mostly sativa	1700
		Total	ca. 9350
Perth	Trifolium[2]	subterraneum	6000
		other spp.	1500-2000
	Ornithopus[2]	spp. (mainly compressus)	500
	Lupin[3]	angustifolius	600
		cosentinii	100
		albus	50
		hispanicus	40
		luteus	20
		others	40

[1]Information supplied by E.D. Higgs.

[2]Information supplied by W.J. Collins.

[3]Information supplied by J.S. Gladstones.

Table 5 - Details of legume collections held by Grasslands Division, D.S.I.R., Palmerston North

Genus	Species	No. of accessions
Trifolium	repens	5000
	pratense	2300
	hybridum	200
	subterraneum	300
	fragiferum	100
	others	700
Medicago	sativa	1000
Lotus	spp.	1700
Ornithopus	spp.	350
Various	spp.	800

[1]Information supplied by M.B. Forde.

it is often regarded, particularly by those in authority, as safe from further danger of being lost. Such complacency is misguided. In fact, there is probably just as much chance of genetic erosion in a gene bank as in the wild situation, unless active measures to prevent this are undertaken.

Maintenance of a genetic resource collection can be a thankless, unrewarding task. Usually only those people with an active interest in a particular species or group are likely to make a realistic effort at maintenance.

Future Needs for Germplasm Exploitation

Australia and New Zealand have an enviable record in the genetic resources field. Extensive collections have been assembled, and computer documentation is well advanced. Good use has been made of the collections, and this high level of usage will continue. Nonetheless, some needs are obvious.

More Support for Genetic Resource Maintenance

In the past, genetic resource work has largely been supported in principle only (e.g., the unfunded situation of the Australian "centres"). The main problem is that maintenance (regeneration) work is so time-consuming and unproductive (in terms of publications and innovative technology). Often the operations are hidden within other programs, and it is hard to realise just what physical and financial resources are involved.

In 1979, R.J. Williams (personal communication) estimated that in the Division of Tropical Crops and Pastures, the involvement in germplasm work was equivalent to 6 full-time workers, but that to adequately fulfill the role of a National Genetic Resource Centre for tropical forages, an additional 4 people would be needed, with a total operating budget of well over $300,000 (in 1983 terms). This operation includes all phases of introduction, quarantine, description, seed production, regeneration, cataloguing, data base handling, and distribution of seed. At that time, the cost to CSIRO for each sample sent out was about $20. The scale and expense of such operations is often not appreciated by those who provide funds nor by those who use the service provided!

The example above is of course an extreme one; operation of collections covering single species, or a small range, will be cheaper, but nonetheless extensive and expensive. In all collections, much material has been or will be lost because of inadequate financial resources.

The Need For More Collections To Be Made

While this may seem very desirable, Bunting (1983) has pointed out that there is little point in making collections if the material cannot be adequately described and maintained. Because seed of wild collections is often of poor quality and only has low numbers of seed per sample, it should be quarantined to produce fresh seed as soon as possible. If this is not done, then the loss of accessions means that the funding of collecting trips is not a very efficient use of resources.

The following suggestions follow Williams (1983). In tropical legumes, the collections held are scarcely adequate for species of known utility and need to be extended to include more species of known value. In the Caesalpiniodeae, there are about 35 genera with 600 species which may have some potential for forage, mostly as browse shrubs. The greatest concentration of potentially useful species in this subfamily is in Africa.

The Mimosoideae contains 19 genera with about 600 species which may have potential. However, alkaloids and other toxic compounds including non-protein amino acids are common in this subfamily.

About 2600 species in 174 genera of the tropical Papilionoideae need to be evaluated. Most of these are herbaceous. Whilst most species related to those already in cultivation are American in origin, significant centres of concentration occur in Africa and Asia for the Tephrosieae, Indigofereae, and Crotolarieae and for subtribes Glycininae and Cajaninae of the Phaseoleae.

R.J. Williams (1983) suggests that highest priority be given to tropical America, especially to those regions not adequately collected. In most parts of the tropics of Africa, America, and Asia, land development is rapid and it is urgent that representative collections of all potentially useful species be obtained before genetic erosion severely reduces the available resource.

On the other hand, for temperate species, Mathison (1983) acknowledges that major resource collections exist for Trifolium subterraneum and some Medicago species. However, he considers the wild annual Mediterranean pasture species are rarely adequately conserved. Because so many of the Mediterranean genetic resources occur in politically volatile regions, priorities for collection and preservation are dictated largely by opportunism. Individuals will undoubtedly have specific needs and priorities.

Research on Methods of Efficient Screening

For some characters, simple biochemical tests are available; others need long-term feeding trials or extensive growing in the field to determine their presence or absence. The problem is not generally one of lack of variation, but lack of precision in detecting such variation. Particularly in perennial species, it may be possible to use seedling characters to predict the performance of fully grown plants.

Research on Storage Methods

While good data are available for optimum storage conditions for grain crops, little is known for forages, particularly tropical legumes. Possibilities other than storage as seed (e.g., tissue culture) may be worth investigating, although with relatively free-seeding plants this may be inefficient. It may be valuable where seed is not available (e.g., perennial Arachis).

Methods of Releasing Variation Contained Within The Collections

Many genera contain large numbers of species, all of which have different characteristics. They should not be thought of as discrete entities, even from a genetic point of view, since hybrids can readily be made between some species or groups of species. Mathison (1983) has pointed out the value of transferring characters between species. However, this is often not easy. It requires knowledge of species relationships and inter-compatibilities, and often of specialised techniques for embryo culture. This knowledge does not exist for all species of interest.

Acknowledgements

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Discussion

Roughley: Germplasm for Rhizobia should be related to legumes, three large collections in Australia—all with similar problems. Rhizobia should be collected with the legume where possible. Collections are inadequate and there is little support for their maintenance, which is essential if the germplasm is not to be lost, contaminated, or change its symbiotic properties.

Bray: There is a need to collect Rhizobia at the same time as the plant.

Rumbaugh: It is often difficult because of soil physical characteristics and terrain to obtain a sample containing Rhizobia.

Roughley: Yes, but even dried samples will provide useful material.

Brougham: New Zealand has not been successful in collaborating with other groups in joint collections to date. New Zealand doesn't have money to mount big collections on its own. Suggested Bray organize proposal for joint collections by all three countries.

Bray: Joint collecting can be useful and certainly avoids duplicating collecting efforts. However, what is important is to try and sort out what is common to all collections—e.g., the same accession would be known by three different numbers in Australia, New Zealand, and the United States. We need to sort out this duplication, as it can be a source of confusion.

Stern: It doesn't matter if some ground is covered repeatedly. Role of USDA as custodian of genetic resource should be acknowledged. Current technology should allow good record keeping and exchange of information. From my experience with subclover, it is best if the breeder does the collection.

Lancashire: The importance of *T. repens* has been stressed throughout this meeting. Have you collected *T. repens* widely with Australia?

Bray: I think Tony O'Brien made some collections but these are not extensive.

Clements: *Trifolium repens* seems to be the "blind spot" in Australia. With big collections of cross-pollinated plants, the problem is how to maintain them and where does money come from? Is it best to keep it with DSIR and CSIRO, or to set up a specific national body charged with sole responsibility of gene maintenance.

Bray: Maintaining each accession in isolation is the ideal system, but costly. Staff hard to get and to keep now for this task with CSIRO and DSIR, and chance of setting up a new national department for gene maintenance is low.

Runge: Some restrictions on germplasm transfer (quarantine) seem to be pointless or too restrictive.

Bray: Yes, but this often reflects lack of knowledge in regard to disease occurrence and transmission.

Germplasm Sources of Forage Legumes Available in the United States

William E. Knight[1]

Abstract

Early introduction of legume species into the United States was by colonists from Europe during the late seventeenth and eighteenth centuries. Plant introduction in the United States evolved through stages, beginning with American consuls overseas who sent back seeds of useful plants to the United States and later with organized plant exploration and introduction. In addition to exploration excursions, forage legumes have been introduced into the United States as the result of seed-exchange programs, direct requests by scientists, or collected in conjunction with exploration of other crop species. The present National Plant Germplasm System is a coordinated network of institutions and agencies (State, Federal, and private) working cooperatively to introduce, maintain, evaluate, catalog, and distribute plant germplasm. Regional Plant Introduction Stations play a vital role in the National Plant Germplasm System. Forage legume accessions are stored and distributed primarily from the North Central (alfalfa), Northeast (perennial *Trifolium* species), and Southern (annual legume species) regional plant introduction stations. The U.S. Department of Agriculture's Soil Conservation Service's Plant Materials Centers assist the regional plant introduction stations in evaluation of plant introductions and, in some cases, make seed increases and participate in cultivar releases. Crop advisory committees for alfalfa and clover and special purpose legumes have been appointed to provide information and advice on germplasm acquisition, evaluation, enhancement, and maintenance. Since 1958, the National Seed Storage Laboratory has served an important role in long-term storage of germplasm and research on seed storage. U.S. germplasm resources are currently being placed in a computer-based information system to provide researchers a means of locating seeds having desirable traits.

Introduction

The inherent genetic plasticity of the various legume species introduced into American agriculture is evident in their widespread and varied use (Cope and Taylor 1984). This plasticity has been exploited by the development of hay and pasture types for a wide range of climatic and edaphic conditions.

The development of adapted cultivars has not been a major problem with either annual or perennial species. Ecotypes have arisen readily after introduction and have provided cultivars for immediate use and germplasm for breeding programs. For example, in alfalfa, *Medicago sativa* L., Hanson and Barnes (1973) described five cultivars developed from early introductions from Germany, Kashmir, Russia, Egypt, and Peru. Most of these have since been replaced with better adapted disease- and insect-resistant cultivars. Similar reports are common for other species as well. In birdsfoot trefoil, *Lotus corniculatus* L., 'Empire' is a selected ecotype found in Albany County, NY (Seaney 1973). Most *Trifolium* species cultivated in the United States have originated from the Mediterranean area.

This paper will address the acquisition, maintenance, and availability of legume germplasm in the United States.

Germplasm Sources

Plant Exploration and Introduction

Australian scientists have provided international leadership in exotic legume germplasm acquisitions, and they have developed ways of maximizing the use of pasture legumes as a source of nitrogen with less dependence on nitrogen-based fertilizers produced from fossil fuels. The success of the Australian introduction effort has been an example to other countries in germplasm acquisition.

Early introduction of legume species into the United States was by colonists from Europe during the late seventeenth and eighteenth centuries. These species moved westward with the settlers; years later, "land races" or ecotypes were identified. This source of germplasm had a major impact on early development and improvement of a number of species and is the only commercial source of germplasm available for some species at the present time. As the demand for legume species for forage and in conservation tillage systems expands, local ecotypes or land races will likely increase in importance unless research is increased on forage legumes.

In the United States, organized plant exploration and acquisition has been more effective in alfalfa than for other legume species. Between 1950 and 1980, only two extensive plant exploration and collection excursions were conducted for *Trifolium* species by U.S. scientists (Gillett and Smith 1984). Both explorations, 1958 and 1977), were confined to southern Europe. Specimens from both collections were deposited into the U.S. Plant Introduction System. The paucity of exploration during this period reflects the reduced emphasis on forage legume research when nitrogen fertilizer was inexpensive and plentiful. Currently, interest is up, and exploration trips are in the planning stage. One such trip into Morocco was conducted by Rumbaugh and Graves in 1983. Other collection excursions are currently being planned.

Seed of forage legumes has been introduced into the United States from northern Africa, Turkey, Iran, Iraq, and the Soviet Union. According to Gillett and Smith (1984), other areas that contain a wealth of useful germplasm, especially perennial types, are Hungary, Yugoslavia, Albania, Romania, and southern Russia. Although specimens have been received from these areas, extensive bilateral explorations should

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be conducted to obtain additional germplasm resources before they become extinct.

Individual Contacts With Scientist Counterparts

Accessions of numerous forage legume species have been introduced into the United States and Canada as a result of individual requests, reciprocal exchange of germplasm, and plant exploration and collection excursions emphasizing other crops (Gillett and Smith 1984). For example, in 1977, numerous samples of Trifolium ambiguum Bieb. were acquired from the Soviet Union by D.R. Dewey while he was on an excursion to collect grass species.

Individual contacts have been fruitful sources of germplasm for a number of species. The late J. Katznelson shared his extensive collections with scientists around the world (Katznelson 1966). An outstanding example of binational cooperation in germplasm enhancement is the exploration by Forbes and Gladstones (Forbes 1975). During this exploration in the western Mediterranean region in 1973, seeds of wild blue lupine, Lupinus angustifolius L., ecotypes were collected from 126 sites to increase the amount of germplasm available for blue lupine breeding in the United States and Western Australia. High percentages of the wild ecotypes were found resistant to gray leaf spot, Stemphylium solani Weber and S. botryosum Walh. (Forbes et al. 1975). Breeding for disease resistance and winter hardiness involved germplasm exchange between scientists in the United States and resulted in winter-hardy and disease-resistant germplasm for both countries (Wells et al. 1980). Subterranean clover, Trifolium subterraneum L.; annual medics, Medicago spp.; and numerous other legumes have been shared with U.S. scientists by Australian scientists, including C. Francis, F. Morley, J.S. Gladstones, P.S. Cocks, and many others. In 1970, samples of seed were brought to the United States from Italy by C.S. Garrison. One was 'Sacromonte' berseem clover, T. alexandrinum L., which, following screening for winter hardiness, has led to the release of a winter hardy cultivar.

Plant Introduction Stations of the U.S. Department of Agriculture Agricultural Research Service

Upon request from research workers, seeds of plant introductions are available in small quantities from the appropriate regional plant introduction station. There are four regional plant introduction stations: the Northeast Regional Plant Introduction Station, Geneva, NY; the Southern Regional Plant Introduction Station, Experiment, GA; the North Central Regional Plant Introduction Station, Ames, IA; and the Western Regional Plant Introduction Station, Pullman, WA. Most Trifolium species are maintained at the Southern and Northeastern Regional Plant Introduction Stations. Annual species are maintained in the Southern region and perennial species in the Northeast region. The primary collection of alfalfa is at the North Central Plant Introduction Station, with some accessions and annual Medicago spp. maintained at Beltsville, MD. State agricultural experiment stations cooperate with the regional stations in accumulating germplasm inventories.

During initial multiplication, plants are observed for agronomic and horticultural characteristics, disease and insect resistance, and other desirable genetic characters. These preliminary data are summarized and published for the convenience of research workers who wish to use the information in requesting germplasm. In addition to the collections in the Northeast, North Central, and Southern Regions, 20 genera with 227 species of special-purpose legumes are maintained at the Western Regional Plant Introduction Station. Some 15,357 accessions make up this collection with Astralagus spp., Cicer spp., Lens spp., Lupinus spp., Onobrychis spp., Phaseolus spp., and Vicia spp., constituting the majority of the Leguminosae accessions. The Southern Regional Plant Introduction Station lists 57 genera of Leguminosae, with 517 species and 15,499 accessions.

U.S. Department of Agriculture Soil Conservation Service, Plant Materials Centers

Soil Conservation Service (SCS) Plant Materials Centers (PMC's) in the various states work closely with the Plant Introduction Stations in the early evaluation of promising germplasm. This cooperative effort has resulted in a number of cultivar releases without modification following evaluation of introduced germplasm. 'Amclo' arrowleaf clover, Trifolium vesiculosum Savi., is an example of this type of evaluation and release of an introduction (Beaty et al. 1965). The PMC's also serve as a source of seed increase of germplasms for evaluation by State experiment stations and other agencies. 'Appalow', a prostrate sericea lespedeza, Lespedeza cuneata Don., is an example of this type of cooperative release (Henry and Taylor 1981).

National Seed Storage Laboratory of the U.S. Department of Agriculture Agricultural Research Service

With the opening of the National Seed Storage Laboratory (NSSL), Fort Collins, CO, in 1958, a national storage program for the permanent preservation and conservation of seed stocks was available for the first time in the history of U.S. agriculture. The seed storage rooms can handle as many as a half million seed lots. Currently, more than 95,000 samples are in storage under carefully controlled temperature and humidity environments.

The NSSL has a twofold mission to preserve valuable seed stocks and to conduct research on aspects of seed viability and storage. Preservation of germplasm is accomplished through the collection of seeds of known value. All agronomic, horticultural, forest, and esthetic types qualify for storage, including obsolete varieties, current varieties, breeding lines, and genetic stocks. Seeds accepted by the laboratory become the property of the Federal Government. The laboratory publishes inventories of its seed stocks. The seeds are available to researchers in the United States when it is confirmed that the laboratory is the only known source of the needed germplasm. Under special conditions, seeds are accepted from and provided to foreign scientists.

The crop characteristics of all seeds stored are recorded on accession cards and placed into an automated data-processing system. This system provides researchers a means of locating seeds having desirable or needed traits.

Crop Advisory Committees and the Germplasm Resources Information Network

Crop Advisory Committees

Crop advisory committees are national working groups of selected Federal, State, and industry specialists providing critical analysis, data, and advice about the activities necessary for effective conservation and use of plant genetic resources within a specific crop or group of related crops of current or potential economic importance. Committees have been appointed for alfalfa, clover and special purpose legumes within the guidelines of the 1979 report of the National Plant Genetic Resources Board to the Secretary of Agriculture entitled "Plant Genetic Resources: Conservation and Use."

In general, these committees provide information and advice to the National Plant Genetic Resource Board in the following broad areas: germplasm acquisition, germplasm evaluation, germplasm enhancement, and germplasm maintenance. At this point, the roles of the committees are still evolving for alfalfa and for clover and special purpose legumes.

The importance of germplasm is expected to receive increased emphasis. The committees will have a vital role to play not only in germplasm enhancement but in other aspects of the National Plant Germplasm System.

Germplasm Resources Information Network

The Germplasm Resources Information Network (GRIN) is a computer-based information system serving the information and operational needs of the Agricultural Research Service's National Plant Germplasm System. The network was developed to provide improved access to, and communication of, information about plant germplasm as well as to improve the maintenance and distribution of germplasm, thereby enhancing the Nation's crop improvement efforts.

The network was developed as a cooperative project between the U.S. Department of Agriculture Agricultural Research Service and the Laboratory for Information Science in Agriculture (LISA) at Colorado State University. The Germplasm Resources Information Project was initiated in 1977 to develop this information network. Technical team members from Colorado State University and U.S. Department of Agriculture have been involved in this joint effort.

The network will contain basic information needed by plant breeders, crop curators, administrators, and others to make decisions regarding their particular activities. The network has three broad categories of information: Registry is the initial information available about an accession when it enters the National Plant Germplasm System, such as the country of acquisition and the collector's name. Characteristic is the observable/measurable traits of the accession such as the agronomic characteristics and the insect and disease resistance. Maintenance is the information needed to ensure that accessions are maintained and available for distribution such as the quantity on hand, storage location, and viability testing dates.

The efficiency of the National Plant Germplasm System will be greatly enhanced as the crop advisory committees develop descriptors and evaluation data to be placed in an automated information system. Locating germplasm with desirable characteristics will then be possible with a minimum of time when requests for seed are received.

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Discussion

Collins: Firstly a comment...I'm reminded that there are "blind spots" with the Australian scene because we cannot get into some of the sites described by Bill Knight. Question is...There has recently been some excitement expressed on cryogenic storage. Have you any comment on this as a method of extending seed life?

Knight: I have no personal knowledge of this, but the advice I have is that there is no need for storage of legumes in expensive storage facilities. Equipment which will hold temperature about minus 20°F is adequate. Research indicates that under these storage conditions, viability remains. In the United States, an ordinary home freezer has been recommended.

Marten: Different pH requirement for alfalfa growth between the United States (pH 6.0 or greater) and Australia and New Zealand (pH 5.5 or thereabouts). Suggest Rhizobia better adapted to low soil pH in Australia and New Zealand than in the United States and that this could be area for future research.

Knight: I agree entirely.

Rumbaugh: I think it is a tremendous idea.

Barnes: Collecting wild germplasm is very expensive, and some organizations feel that better value for money is received by searching within existing collections for traits such as disease resistance. Can the speaker give his views?

Knight: There are two aspects to this. One is where you require a trait to solve an immediate problem, and the other aspect is insurance against unknown future requirements. It is necessary to do both.

Brougham: I agree and suggest both pathways should be followed.

Stern: How do you measure plasticity of species?

Clements: White clover is continually coming into Australia and therefore no problem. Tropical legumes have a narrow base in Australia, and there is a need to increase base.

Brougham: White clover for New Zealand has come in from the Mediterranean areas to ensure plasticity of species.

Sheath: While there is gain in broadening the genetic base, could you comment on exploring the local variation? There are obvious benefits to cost effectiveness, and much of the N.Z. and Australian subclover programs are based on local collection.

Knight: This is an excellent point and is reinforced by experience in the Southern States with alfalfa when disease decimated stands. About 100,000 acres were grown in the Mississippi Delta in the 1930-40 period. Collection by a pathologist of survivors provided the base for the disease-resistant Delta cultivar.

Easton: Almost all plant breeders would prefer to work with their own material. However, a two-stage approach with widening the resource seems most appropriate.

Brougham: Earlier discussion was on performance of lucerne at pH 5.5. I should point out that we have little data on yield of N.Z. lucerne stocks at lower pH.

Marten: Yes, but the persistence is interesting.

Brougham: There are many examples where it is necessary to bring material in from overseas because the desirable factor, e.g., pest resistance, is not present in local collections. Even with extensive collections for white clover and a long history of introduction, it has proved necessary to obtain genetic material from, e.g., the Mediterranean to develop improved cultivars.

Breeding to Improve Alfalfa: Historical Progress and Future Prospects

M. D. Rumbaugh and G. H. Heichel[1]

Abstract

U.S. alfalfa (Medicago sativa L.) forage yields have increased from about 5.00 Mg/ha in 1919 to more than 7.00 Mg/ha in 1980. The rate of gain in yield has shown no signs of abating. Yield trials in nearly optimum environments indicate that there has been a 22% rise in genetic yield potential to 22.4 Mg/ha since 'Vernal' alfalfa was released in 1953. Comparison of the average national yields for the last complete decade (6.5 Mg/ha) with the potential yields shows that only 29% of the genetic potential of the crop has been realized. Yields of alfalfa are limited more by diseases, insects, and nematodes than are the yields of grain, root, and tuber crops. However, some notable advances in disease and insect resistance have occurred. Among the physical stresses, drought is the most limiting to yields of alfalfa. Selection of improved germplasm based on use of physiological and biochemical traits has been attempted. Traits associated with carbon and nitrogen assimilation are composed of complex interdependent subprocesses that are quantitatively inherited but poorly suited to phenotypic evaluation. They are extraordinarily sensitive to the environment and stage of plant development. Although physiological and morphological traits can be improved by breeding, the resultant gain in agronomic performance is accomplished more efficiently by conventional methodology. Such research has increased the understanding of how pathways of carbon and nitrogen assimilation are interrelated and regulated and has provided an important framework of basic knowledge about the organismal biology of alfalfa.

Introduction

Improvements in alfalfa (Medicago sativa L.) science, technology, and management have brought about major increases in the area in production, the forage yield per unit of land area, and in the value of this crop to U.S. agriculture. Land area in alfalfa production tripled from 3,494,790 ha in 1919 to 10,638,945 ha in 1980. Yields rose dramatically from about 5.00 to more than 7.00 Mg/ha during that time. Mean annual forage yield (Mg/ha) for the Nation can be described by the quadratic function

$$Y = 4.92 - 0.0397X + 0.0012X^2,$$

where X is the number of years since 1918. The rate of gain in yield shows no signs of diminishing. The market value of the major alfalfa products grown in the United States each year in the 1979 to 1981 period is estimated to have been 5.5 billion dollars (based on statistics in U.S. Department of Agriculture, 1982).

Breeding for Agronomic Traits

Alfalfa breeders have assisted other scientists in making these yield gains possible. For example, development of high levels of anthracnose (Colletotrichum trifolii Bain) resistance in the early 1970's resulted in a 7% yield advantage of resistant over susceptible strains (Elgin et al. 1981). An examination of alfalfa cultivar and germplasm descriptions (Miller and Melton 1983) showed that recent releases were often resistant to several diseases and insects. With the exception of one germplasm selected for resistance to salinity (Dobrenz et al. 1983), none of the newly developed and released alfalfas were intentionally bred for resistance to the specific physical, chemical, and climatic factors limiting productivity or restricting the area in which the crop is economically successful. Current breeding strategy emphasizes reselection of adapted germplasm for pest resistance, with the assumption that environmental constraints to productivity will be alleviated primarily by management technology. However, phenotypic selection of plants and clones in nurseries and of populations in forage yield trials are a part of most breeding programs. These steps evaluate the integrated impact of all environmental and genetic effects and undoubtedly lead to improvement in resistance to constraints other than those due to diseases and damaging insects. Although there have been no germplasm releases for tolerance to the following stresses, we know of research programs in which tolerance to ozone, to soluble aluminum in soil solution, to frequent cutting, and to frost heaving have been investigated. In other programs, selection for increased concentration of reduced nitrogen in herbage or in roots plus crowns is underway (see G.H. Heichel and Laura S. Brophy, "Role of the Legume in the Legume-Rhizobium Symbiosis," earlier in this proceedings). Selection for the appropriate winter-dormancy response is important in the Midwestern United States.

The magnitude of genetic gain in yield since 1953 was clearly indicated by trial data from Michigan where 12 recently released cultivars outperformed the older check, 'Vernal', by an average of 22% when soil fertility and moisture were near optimal (Tesar 1983). Some breeders have successfully emphasized traits imparting superiority when alfalfa is grazed rather than achieving increased hay yields (Heinrichs 1963).

Yield Constraints

Crop growth and development cannot be improved independently of the limitations of the environment. Crop yield is an economic expression of a genetic system operating within the constraints imposed by a variable environment. The objectives of plant breeders are to affect genetic changes which result in gains in crop yield potential, in yield stability, or in yield quality. The historical approach was, and often still is, to first optimize the environment and then to select genotypes expressing their potential within the

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environment as completely as possible. While a carefully controlled and nearly optimal test environment will allow expression of maximum genetic potential, selected genotypes from such tests may not be the most desirable for stressful environments. Selection of plants to yield well in usually stressful environments would be more conservative of natural resources than amelioration of the causes of the stresses.

Boyer (1982) estimated the impact of environmentally induced stress on yield of eight major U.S. grain, root, and tuber crops. He compared the highest known to average yields. Record yields were three to seven times the average. It was apparent that modern cultivars had the genetic potential for very high levels of yield but that yield usually fell far short of the potential. Diseases, insects, and weeds accounted for 4.1%, 2.6%, and 2.6% of the difference between potential and average yields, respectively. Other unspecified but unfavorable factors including less than optimum management practices reduced yields by 68.5% compared with the record yields.

Similar computations for alfalfa show a greater difference between potential and average yields. Alfalfa has a yield potential of approximately 22.4 Mg/ha (Tesar 1983). Average U.S. yield during the decade of 1970-79 was 6.5 Mg/ha or only 28.9% of the genetic capability of modern cultivars. It was estimated that disease, insects, and nematodes reduced U.S. alfalfa forage yields by 24%, 15%, and 5%, respectively, each year (App and Manglitz 1972, Graham et al. 1972). Other factors account for about 27% of the difference between attained and potential yields.

Insurance indemnity experience is an excellent indicator of the causes of catastrophic crop losses in the United States (table 1). Among the physical factors most limiting to yields, drought is the single most important and accounts for 40% of all payments (U.S. Department of Agriculture, 1982). Approximately 5% of U.S. farmland is irrigated. Known water resources indicate that no more than 10% of all U.S. farmland will be irrigated in the future without significant advances in irrigation technology or plant growth requirements. Drought will remain the most important environmental factor limiting alfalfa yields in the Great Plains and Western States, and drought resistance will remain a major objective of plant breeders in semiarid and arid climates (Asay and Johnson 1983, Carlson and Ditterline 1981, Sullivan 1983).

Response to Selection

Plant breeders continue to be perplexed by the need to select plant populations which will be grown in a range of environmental circumstances. Gain from mass selection in one environment, a test environment, can be expressed as a function of the intensity of selection and the narrow sense heritability of the trait in that environment.

$$\Delta G_i = (K_i)\,(\sigma_{p_i})\frac{(\sigma^2_{g_i})}{(\sigma^2_{p_i})}$$

where ΔG_i is the increment of genetic gain for yield in the ith environment,

K_i is the selection differential or the difference between the population mean and the mean of the selected plants growing in the ith environment, expressed in standard measure,

$\sigma^2_{g_i}$ is the additive genetic variance of yield in the ith environment, and

$\sigma^2_{p_i}$ is the phenotypic variance of yield in the ith environment.

Table 1 - Distribution of crop loss insurance indemnities in the United States from 1939 to 1979

	Proportion of payments (%)		
		Forage crops	
Cause of crop loss	All crops 1939-79	Seedling 1978-1979	Production 1979
Drought	39.9	63.4	36.4
Excess water	16.8	19.5	2.9
Cold	13.8	.8	36.8
Hail	12.1		
Wind	6.8	.8	
Insects	4.3		23.9
Diseases	2.8		
Flood	2.1		
Other	1.4	15.6	

From: U.S. Department of Agriculture (1982).

Effect of a Variable Environment

If selection is accomplished in the ith environment but the progeny are grown in the jth environment, a target environment, and i≠j,

$$\Delta G_j = (K_i)\,(\sigma_{p_i})\frac{(\sigma_{g_{ij}})}{(\sigma_{p_i} \cdot \sigma_{p_j})},$$

where $\sigma_{g_{ij}}$ is the genetic covariance between yield in the ith and jth environments.

The term $\dfrac{\sigma_{g_{ij}}}{\sigma_{p_i} \cdot \sigma_{p_j}}$ is the coheritability of yield in the two environments.

It has limits of -1 and +1 and is free of metric (Nei 1960). If coheritability is positive for all combinations of the test environment and all possible target environments, the selection program will result in yield increases in each environment

and in mean yield. If coheritability is negative for one or more target environments, yields in those environments will decline and mean yield may decrease. A plant breeder can guard against this eventuality by careful definition of the range of target environments and choice of test environment. Alternatively, he may expend more of his program resources by testing in more than one environment chosen to represent the range of conditions in the target environments. In the latter case, he will select for high mean yield. Rosielle and Hamblin (1981) showed that selection for mean productivity generally increased mean yields in both stress and nonstress environments. Selection for tolerance to stress will generally result in a reduced mean yield in nonstress environments and a decrease in mean yield. Selection for tolerance to extreme levels of drought stress may not be effective because the observed variation is often entirely nongenetic in origin (Rumbaugh et al. 1984).

Breeding for Physiological/Biochemical Traits

The great surge in research in organismal (whole plant) physiology of crop plants that commenced during the 1960's and continued through the 1970's provided several examples of apparent genetic control of physiological and biochemical traits, PBT (Wallace et al. 1972). This evidence, coupled with concern that a yield plateau was being approached in many crops (NAS 1975), led to the hypothesis that breeding for PBT would enhance the efficiency of progress of breeding crop cultivars with improved agronomic attributes.

Definitions and Assumptions

In contrast to selection for agronomic traits in which the expression of genes is revealed in the phenotype, selection for PBT usually involves measuring the rate or duration of physiological or biochemical processes that are evident in the phenotypes. This must be differentiated from selection for morphological traits (Barnes 1983), which are measurable expressions of plant form or structure indicating the onset or termination of physiological or biochemical processes or controlling their rate or duration. A key assumption that is nearly always implicit in use of PBT in a breeding program is that the rate or duration of the physiological or biochemical process "limits" yield, quality, or agronomic performance at least during the stage of development that the measurement is made and often over the entire growing season.

Criteria for Use in Breeding Programs

Several criteria should be met in using PBT in plant breeding programs (for example, Simpson 1981, Mahon 1983): the trait must be theoretically beneficial to productivity, quality, or agronomic performance; the traits should be easily and inexpensively assayed and nondestructive to the plant; there must be genetic variability among genotypes in expression of the trait and heritability among generations; the genetic control of the trait should be generally understood; and the trait or one of its correlated attributes must be phenotypically expressed in large-scale field trials. These criteria are seldom all met in programs, including breeding for PBT.

Examples

There have been several attempts to improve agronomic performance of many crops, including alfalfa, by breeding for traits associated with carbon and nitrogen assimilation, two key interrelated processes in growth and yield (fig. 1). Most approaches have modified one of the two processes at the enzyme or organ level (10^0 to 10^3 genes) and have evaluated the outcome on an equivalent or higher level of organismal complexity (Heichel 1982, Heichel et al. 1983).

Physiological and biochemical traits are hierarchical in the same sense as morphological yield components (Duarte and Adams 1963). Like morphological yield components, the determination of genetic control and of agronomic benefit is easier for processes causally closer to the agronomic outcome, yield, than for those nearer the initiation of the hierarchy. A portion of figure 1 has been redrawn as a conventional path diagram (fig. 2). Selection for the physiological trait growth rate (X_1) rather than for phytomass (Y) would be expected to alter phytomass by an amount ΔY, but the extent of change is difficult to predict without a complete understanding of the quantitative relationships among the variables. Y will depend upon both direct and indirect causal relationships or paths. The coefficient of multiple determination indicates the complexity of the associations:

$$R^2_{y\cdot 1,2} = p^2_{y1} + p_{y1}p_{y2}r_{12} + p_{y1}p_{y2}r_{12} + p^2_{y2}$$

ΔY may assume either positive or negative values. Similar but more obscure results will occur if the trait used for selection is further removed from yield or phytomass. Selection for carbon assimilation (X_3) will also change phytomass (Y) in both direct and indirect ways. The coefficient of determination will be the following:

$$\begin{aligned} R^2_{y\cdot 1,2,3,4} &= p^2_{y1}p^2_{13} + p^2_{y1}p_{13}p_{14}r_{34} + p_{y1}p_{y2}p_{13}r_{23} \\ &+ p^2_{y1}p_{13}p_{14}r_{34} + p^2_{y1}p^2_{14} + p_{y1}p_{y2}p_{14}r_{24} \\ &+ p_{y1}p_{y2}p_{13}r_{23} + p_{y1}p_{y2}p_{14}p_{24} + p^2_{y2} \end{aligned}$$

It is apparent that the response in phytomass due to selection for carbon assimilation is not easy to predict even when, as in this example, residual effects are not considered.

Status of Research

There has been no clear evidence from any of these programs that breeding for traits associated with carbon and nitrogen assimilation has improved the efficiency of cultivar development. The physiological, biochemical, and genetic analysis that has occurred demonstrate that traits associated with carbon and nitrogen assimilation are: composed of complex interdependent subprocesses; quantitatively inherited; often poorly suited to phenotypic evaluation; extraordinarily sensitive to environment, variably expressed depending upon stage of plant development; improved by breeding, but without improving yield, quality, or agronomic performance more efficiently than by conventional

methods; rarely yield-, quality-, or performance-limiting; and expensive to measure in numbers sufficient for use in a breeding program.

Although the assumption that one or several PBT limit agronomic performance is yet unproven, there have been two distinct scientific benefits to alfalfa improvement from this research. Breeding for traits associated with carbon and nitrogen assimilation, combined with complementary physiological and biochemical research, has increased the understanding of how assimilatory pathways are interrelated and regulated. Furthermore, breeding for PBT is an important experimental approach in the dissection and analysis of this developmental and organismal biology of alfalfa and other economic crops.

Tissue Culture and Molecular Biology

Our survey of possible future changes in alfalfa breeding would be incomplete without briefly considering the potential role of tissue culture and of molecular biology methodologies in alfalfa improvement, because these techniques will be used to amplify the efforts to breed for PBT. Alfalfa strains amenable to tissue and protoplast culture are known (Bingham et al. 1975, Johnson et al. 1984, McCoy and Bingham 1977) and have been used in selection for salinity tolerance (Croughan et al. 1978). More recently, root nodules of alfalfa have been successfully cultured (Vance and Johnson 1982) to probe mechanisms of host-rhizobial compatibility. In an attempt to improve the amino acid balance of alfalfa, variant cell types which overproduce specific amino acids have been sought (Reisch et al. 1981). Selection for resistance to herbicides has been attempted in the private sector. Advances which are single-gene dependent, such as herbicide resistance, should come earlier than answers to problems such as yield and drought resistance, which are controlled by more than one gene (Sirkin 1984). These are exciting initiatives whose time to application cannot be forecast with certainty. Nevertheless, like breeding for PBT, use of tissue culture and molecular biology methods is certain to become an important research tool in alfalfa biology.

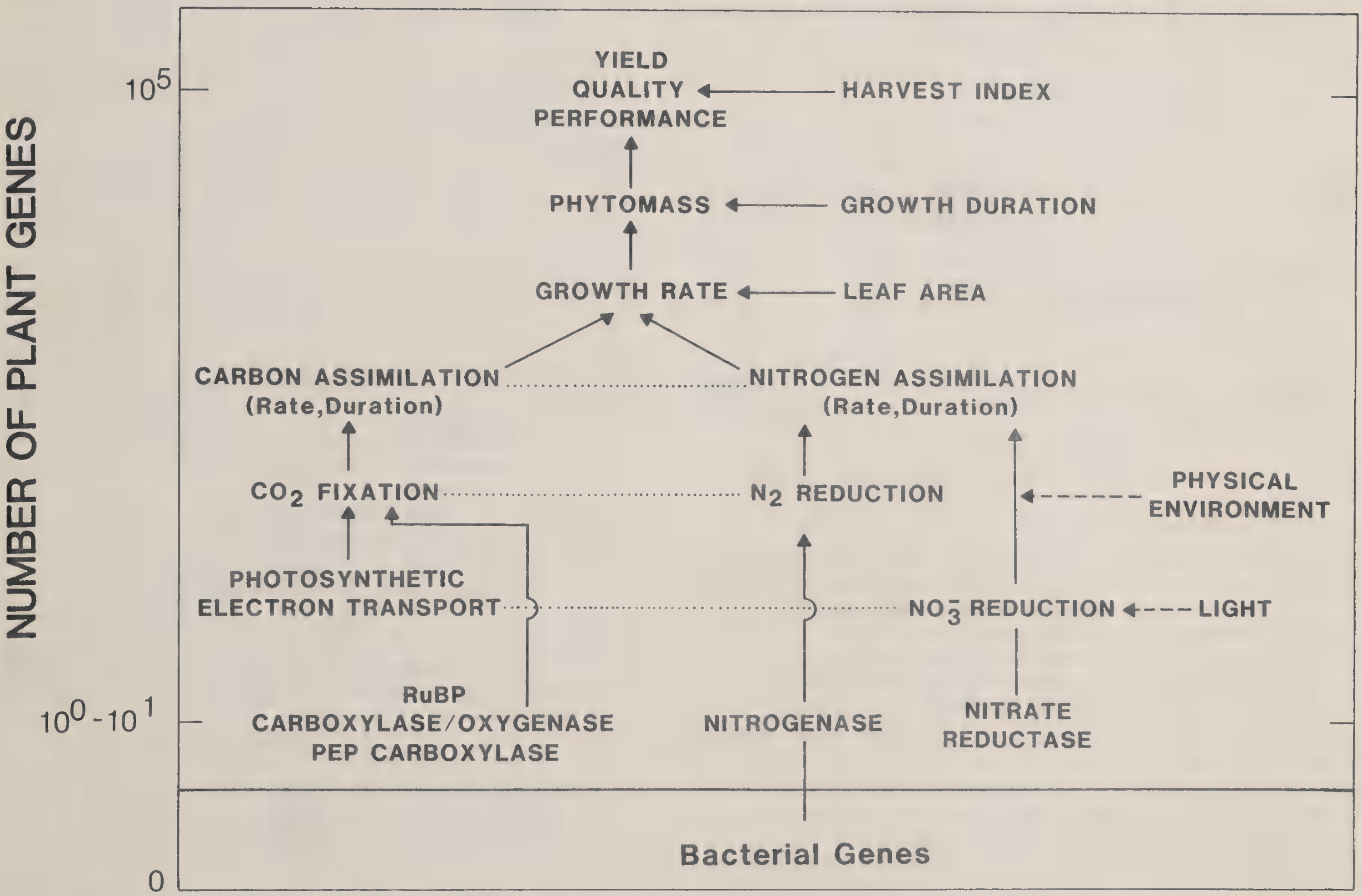

Figure 1--Interrelations of physiological and biochemical traits with C and N assimilation and with crop yield. Traits are arrayed in horizontal strata, commencing initially with the activities of key enzymes, then progressing through more complex electron transport and substrate reduction reactions to culminate in assimilation, growth, and yield. Vertical progression through the diagram illustrates increasing complexity of genetic control, from enzymatic processes controlled by 1-10 genes to yield controlled by ca. 10^5 genes. Vertical solid lines designate principal routes of C and N assimilation. Horizontal dotted lines above the enzyme level connect metabolic events of similar complexity. Dashed lines and arrows represent external factors mediating expressions of traits.

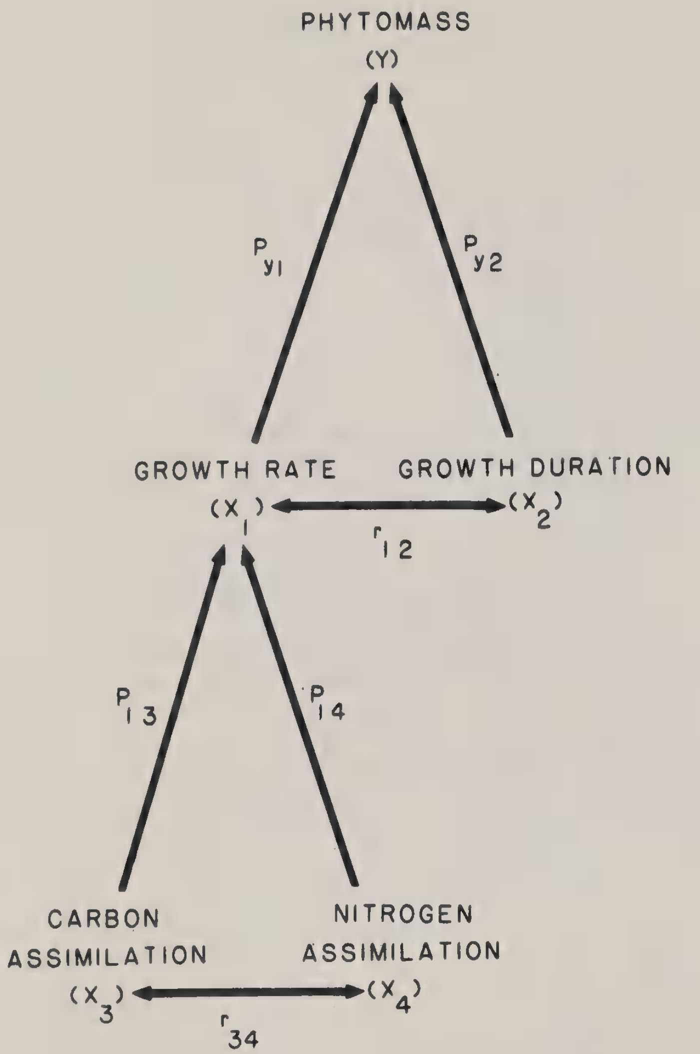

Figure 2—A causal path analysis diagram predicting phytomass.

Future Research

The future genetic improvement of alfalfa will undoubtedly rely upon a clearer understanding of how the expression of desirable genes is controlled at various stages of growth and in different environments. A closer scientific collaboration between conventional breeding and genetics and physiology, biochemistry, and molecular biology is anticipated. This should be a fruitful approach to understanding the genetic control of quantitative traits and manipulating them for plant improvement. We envisage an advancement from recognition of potential (for example, Wallace et al. 1972) to proof of concept in the near future.

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Discussion

Marten: Will it be possible to breed cultivars which are more water-use efficient and still retain good productivity?

Rumbaugh: Yes. Research is proceeding in this. If you need to irrigate to obtain good production but are running short of water, then this approach is critical. Work by Bill Melton at Las Cruces, NM is producing encouraging results.

Brougham: Problems of confidentiality, secrecy, etc., in the area of new breeding techniques is undesirable and should be discussed during this meeting.

Rumbaugh: Yes, I agree.

Runge: Have you had good cultivar selection from line source system, where differential water stress is applied to the same cultivar?

Rumbaugh: We have not been going long enough to tell yet.

Runge: I tried burying plastic sheet at differing depths in a variable rainfall area. It is important to select plants under differential water stress.

Clements: U.S. breeders seem to be mainly breeding for insect and pest resistance. When will this work with physiological and biochemical yield components get under way?

Rumbaugh: Industry breeders will be preoccupied with pests and will not get onto physiological and biochemical yield components for 10 years. Physiological approaches to increasing yield will remain with agencies such as USDA until commercial firms see it as giving a return on money invested.

Breeding to Improve Forage Legumes Other Than Alfalfa in the United States

William E. Knight[1]

Abstract

The wide range of diverse legume germplasm available for general and special-purpose use in the United States indicates the potential exists to maximize forage legumes for energy-efficient animal production. Breeding programs and objectives for forage legumes other than alfalfa are identified and discussed briefly. Extensive research is in progress on red clover, Trifolium pratense L., and white clover, T. repens L. Standard breeding techniques are used in improving these species. Additionally, the recent development of embryo-rescue techniques in interspecific hybridization has stimulated new research to incorporate desirable characteristics into existing cultivars. Arrowleaf clover, T. vesiculosum Savi.; berseem clover, T. alexandrinum L.; crimson clover, T. incarnatum L.; and subterranean clover, T. subterraneum L., are in extensive programs to develop germplasm with insect, virus, fungal pathogen, and nematode resistance. These species are important components of year-around grazing systems in the South. Birdsfoot trefoil, Lotus corniculatus L., is becoming important, and an extensive program in Missouri is devoted to improvement of this species. In the West, research is concentrated on cicer milkvetch, Astragalus cicer L.; sainfoin, Onobrychis viciifolia Scop.; Utah sweetvetch, Hedysarium boreale Nutt.; and annual medics, Medicago spp. Improved cultivars have been released, and germplasm under development promises to extend the range and usefulness of this species. Researchers in Florida are evaluating many accessions of tropical forage legumes representing 12 genera. This productive area of research has developed promising material for southern Florida and coastal Louisiana and Texas.

Introduction

The development of adapted forage legume cultivars has been successful for both annual and perennial species. Ecotypes arose readily after introduction and provided cultivars for immediate use and germplasm for breeding programs (Cope and Taylor 1984). Several major forage legume species are widely adapted to the climate and soils of the United States; early efforts in cultivar development identified types for areas with relatively minor climatic and edaphic differences from those of the center of origin of the species. Geneticists and plant breeders have successfully developed forage legume cultivars with improved characteristics. Development of some of these improved cultivars spanned 25 years. With increased emphasis and more widespread use of forage legumes, it is imperative that cultivar development efforts by public and private plant breeders be accelerated to avoid excessive losses from an inevitable buildup of insect and disease pests.

Presently, the general objectives of legume breeding programs are (1) to develop germplasm and/or cultivars with improved yield and quality; (2) to improve persistence and reliability through development of germplasm that is winter hardy, drought tolerant, and insect and disease resistant; and (3) to improve seed production and reseeding (annuals). A few programs are also emphasizing N_2 fixation as a breeding objective. A coordinated team approach to these objectives is needed to shorten cultivar development time. Forage legume improvement programs in the United States other than those for alfalfa (Medicago sativa L.) will be reviewed in this report.

Red Clover

Red clover, Trifolium pratense L., is naturally cross-pollinated and basically self-incompatible because of the gametophytic incompatibility system. Therefore, natural selection and breeding procedures, such as mass selection, maternal-line selection, recurrent selection, and hybridization, have contributed to the development of cultivars or strains in commercial use (Taylor and Smith 1979). Recent comprehensive reviews provide detailed discussion of breeding objectives, procedures, and accomplishments in red clover breeding and genetic research in the United States (Taylor and Smith 1979, Cope and Taylor 1984, and Smith and Taylor 1984).

There are two extensive red clover improvement programs in the United States, one at Lexington, KY, and the second at Madison, WI. Objectives of red clover improvement are increased yield and persistence; improved winter hardiness; development of fundamental cytogenetic knowledge of Trifolium species; and increased resistance to viruses, root and foliar diseases, and nematodes. Selection for persistence and disease resistance is also conducted by scientists at University Park, PA; Tifton, GA; and Gainesville, FL.

Currently, two of the most prominent cultivars in the United States are 'Arlington' and 'Kenstar'. Arlington was a joint release by the U.S. Department of Agriculture and the Wisconsin Agricultural Experiment Station (Smith et al. 1973). It is highly resistant to powdery mildew, Erysiphe polygoni DC., and northern anthracnose, Kabatiella caulivora (Kirsh. Kavak.), and is adapted to the North Central and Northeast United States. Kenstar was a joint release by the Kentucky Agricultural Experiment Station and the U.S. Department of Agriculture (Taylor and Anderson 1973). It is highly resistant to southern anthracnose, Colletotrichum trifolii Bain, moderately resistant to bean yellow mosaic virus, and adapted to the southern clover region of the United States. Several widely used cultivars have also been released by private companies. The Kentucky and Wisconsin programs have also been active in interspecific hybridization and ploidy levels in red clover (Taylor and Smith 1979, Phillips et al. 1982). Germplasm of T. sarosiense x T. alpestre and

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T. medium x T. sarosiense has been released (Taylor and Quesenberry 1978a, 1978b).

White Clover

White clover, T. repens L., is widely adapted for use in pastures in the United States (Gibson and Hollowell 1966, Leffel and Gibson 1973, Carlson et al. 1984). The importance of white clover is indicated by the existence of improvement programs in Alabama, Florida, Georgia, Idaho, Louisiana, Mississippi, North Carolina, and South Carolina. Extensive research on this species is conducted in the Idaho, Mississippi, North Carolina, and South Carolina programs.

General objectives in white clover research are similar to those in red clover programs, with major emphasis on persistence. To obtain persistence, resistance to viruses, root diseases, and nematodes must be incorporated into cultivars. Prior to retirement, P.B. Gibson led an extensive and productive multidisciplinary program on white clover at Clemson, SC. This research team produced 11 interspecific hybrid combinations, 8 for the first time, among 5 species of clovers. Two species of clovers, successfully hybridized with white clover, now offer improvement in white clover by their genetic contributions of short internodes, tolerance to virus diseases, larger seed, woodier roots, and tolerance to drought and shallow soils. This progress in interspecific hybridization in clovers represented the most promising advance in the history of white clover improvement (Chou and Gibson 1968, Gibson and Beinhart 1969, Gibson et al. 1971, Gibson and Chen 1975). A technique was developed at Clemson to screen thousands of white clover plants for resistance to root-knot nematodes (Baxter and Gibson 1959). Resistant clones were intercrossed at Prosser, WA, and a root-knot-nematode-resistant white clover germplasm was released to public and commercial white clover breeders as SC-1 (Gibson 1973).

Another example of improved germplasm resulting from white clover research is a forthcoming virus-resistant germplasm release. This material was developed through a five-State cooperative project. Plants were screened by mechanical inoculation, aphid inoculation, and field tests for resistance to alfalfa mosaic virus, peanut stunt virus, and clover yellow vein virus. Further field screening identified 44 clones resistant to these viruses in all tests. A germplasm release of this material will be made shortly. Other promising white clover germplasm includes Florida XP-2 developed by the Florida Agricultural Experiment Station and the Brown Loam germplasm developed for drought tolerance by the Mississippi Agricultural Experiment Station and the U.S. Department of Agriculture.

The predominant white clover cultivars in the South are the ladino types 'Regal' and 'Tillman' and the intermediate types 'Louisiana S-1' and 'Nolin's Improved'. Regal is a five-clone synthetic released by the Alabama Agricultural Experiment Station in 1962 (Johnson et al. 1970); Tillman, a six-clone synthetic, was released by the South Carolina Agricultural Experiment Station and the U.S. Department of Agriculture in 1965 (Gibson et al. 1969). Louisiana S-1, a five-clone synthetic released by the Louisiana Agricultural Experiment Station in 1952 (Hollowell 1958), and Nolin's Improved, a naturalized cultivar, behave as reseeding annuals in the Southeast. Ladino white clover is used in pasture mixtures in the Northeast, North Central and Pacific Coast regions. The New Zealand cultivar 'Grasslands Huia' is recommended in the Pacific Coast region.

Birdsfoot Trefoil

The history and development of birdsfoot trefoil, Lotus corniculatus L., cultivars in the United States are reviewed in detail by Seaney and Henson (1970) and by Seaney (1973). The primary objective of breeding programs in birdsfoot trefoil has been to increase forage yields for pasture and hay. Specific breeding objectives to accomplish this goal have involved the improvement of seedling vigor, resistance to root rots, winter hardiness, and rapid growth recovery after cutting. The most intensive research is P.R. Buselinck's program in Missouri. Research is directed toward development of insect- and disease-resistant germplasm and a better understanding of the elusive nature of trefoil longevity as affected by disease, management, and environment and their interactions. Interspecific hybridization in Lotus spp. constitutes a part of this improvement program. Research is in progress at the U.S. Pasture Research Laboratory, University Park, PA, for disease-resistant germplasm; numerous other locations throughout the United States have evaluation programs in progress.

Interest in birdsfoot trefoil has increased in the South. Breeding programs in Alabama, Georgia, and Kentucky have developed advanced generation germplasm, for release when adequate seed stocks are developed. 'Fergus' is a release from Kentucky, 'AT-P' from Alabama, and 'Georgia-1' from the Georgia Agricultural Experiment Station (Pederson and Knight 1983). These cultivars have been developed for improved forage yield, seed yield, persistence, and pest resistance. Recent evaluation indicates that none of the available germplasm sources will persist in central and southern Alabama because of root diseases and nematodes (Hoveland et al. 1982).

Annual Clovers

Breeding objectives in annual clovers are similar--increased resistance to viruses, root and crown diseases, and nematodes (Pederson and Knight 1983, 1984). The major annual species used in the United States are reviewed in detail in "Trifolium Science and Technology" to be published in 1984 as a monograph by the American Society of Agronomy.

Arrowleaf Clover

The objectives of arrowleaf clover, Trifolium vesiculosum Savi., research are to obtain early emergence with uniform stands; increase late spring persistence; improve drought tolerance; and increase resistance to viruses, root diseases, and nematodes. Virus diseases are a major problem and reduce the clover stand, both by direct effect and by increased susceptibility to secondary

pathogens through reduced plant vigor. Initial research on arrowleaf clover indicates that virus diseases and nematodes are the major constraints to success with this species (Knight and Hoveland 1973, Nichols et al. 1981, Miller and Wells 1984).

Florida, Georgia, Louisiana, Mississippi, and Texas are involved in arrowleaf clover improvement (Pederson and Knight 1983). The Florida program emphasizes nematode resistance. Host-plant-resistance studies are conducted in Mississippi to obtain resistance to viruses and to two Phytophthora diseases. The standard cultivars of arrowleaf clover are 'Amclo', 'Yuchi', and 'Meechee'. Amclo, an early maturing cultivar, was released by the Georgia Agricultural Experiment Station and the U.S. Department of Agriculture (Beaty et al. 1965). Yuchi, a later maturing type, was released by the Alabama Agricultural Experiment Station (Hoveland 1967). Meechee, the latest maturing and most winter hardy cultivar, was released by the Mississippi Agricultural Experiment Station and the U.S. Department of Agriculture (Knight et al. 1969).

Berseem Clover

Berseem clover, Trifolium alexandrinum L., is a winter annual clover that is in the improvement programs of California, Florida, Louisiana, Mississippi, and Texas. Presently, there are no cultivars adapted to the Southeast except Florida, since existing cultivars do not have adequate winter hardiness. The main objective of berseem clover improvement in Mississippi is to increase the winter hardiness of the species. Secondary objectives include developing resistance to leaf diseases and improving rate of recovery after clipping. In California, emphasis is given to yield and recovery after clipping. A winter-hardy berseem clover has been developed in Mississippi from plants of the Italian cultivar 'Sacromonte' that survived field temperatures as low as -15° and -18°C. A release of this material has been proposed (Knight and Watson 1984).

Crimson Clover

Research on crimson clover, Trifolium incarnatum L., improvement is conducted in Florida, Kentucky, Louisiana, Mississippi, and Texas (Pederson and Knight 1984). Crimson clover improvement has been reviewed in detail by Knight and Hollowell (1973), Knight and Hoveland (1973), and Knight (1984).

The objectives of crimson clover research are to improve N_2 fixation; improve fall growth; reduce seed shatter and lodging; and increase resistance to the clover head weevil, Hypera meles Fab., viruses, root diseases, and nematodes. The clover head weevil is a major insect problem on crimson clover. Feeding by this insect reduces reseeding and may result in poor stands in subsequent years. Research in Mississippi should develop weevil-resistant germplasm. The program in Florida is making progress on nematode-resistant genotypes. The predominant cultivars are 'Dixie', 'Chief', 'Autauga', and 'Tibbee'. Dixie was released in 1946 by the Georgia Agricultural Experiment Station and the U.S. Department of Agriculture (Hollowell 1953). Chief, 'Frontier', and Tibbee were released by the Mississippi Agricultural Experiment Station and the U.S. Department of Agriculture (Hollowell 1960; and Knight 1963 and 1972, respectively).

Subterranean Clover

Subterranean clover, Trifolium subterraneum L., improvement is included in breeding programs in California, Georgia, Louisiana, Mississippi, and Texas (Knight et al. 1982, McGuire 1984). Much of the research on subterranean clover in the United States has been directed toward the evaluation of the wide array of germplasm generated through decades of research on this species in Australia. In the Southeastern United States, selection within late-maturing types for hard-seeded strains is in progress, to provide more reliable reseeding. The early maturing types are being evaluated in California for hard seed and improved forage production. A subclover ecotype with increased adaptation to the Southeast has been developed by the Mississippi Agricultural Experiment Station and the U.S. Department of Agriculture. This ecotype was selected from a stand that persisted for over 30 years from an original seeding of the Australian cultivars 'Mt. Barker', 'Bacchus Marsh', and 'Tallarook'. This subclover will be released as germplasm or as a cultivar in the near future.

Ball Clover

Interest in ball clover, Trifolium nigrescens Viv., has increased in Alabama, Mississippi, and Louisiana (Pederson and Knight 1983). In Alabama, breeding objectives are increased forage and seed yield and improved pest resistance. The Alabama Agricultural Experiment Station plans a germplasm release in the near future. In Mississippi, a farmer variety 'Segrest' was recently increased and is being evaluated in regional variety tests.

Lespedeza Species

Both perennial and annual lespedezas have been in improvement programs in the United States. Currently, there are no active breeding programs on the annual lespedezas striate, Lespedeza striata (Thumb.) Hook and Arn., and Korean, L. stipulacea Maxim. (Pederson and Knight 1983). Alabama, Kentucky, Louisiana, and North Carolina are involved in sericea lespedeza, L. cuneata (Don.), improvement. The most extensive breeding program has been in Alabama, and many States are evaluating both annual and perennial species. The main objectives of sericea lespedeza research have been to develop low tannin content and to increase nematode resistance. Until recently, the predominant cultivars of sericea lespedeza were 'Arlington', 'Serala', and 'Interstate'. Serala and Interstate were released by the Alabama Agricultural Experiment Station in 1962 (Donnelly 1965b) and 1969 (Donnelly 1971). In 1978, three cultivars were released. 'Serala 76' and 'Interstate 76' released by the Alabama and Georgia Agricultural Experiment Stations and the U.S. Department of Agriculture contained nematode resistance and other improvements not in the original cultivars (Donnelly and Minton 1979). 'Appalow', the first prostrate lespedeza, was released by the Kentucky Agricultural Experiment Station and the U.S. Department of Agriculture

(Henry and Taylor 1981). In 1980, 'AU Lotan' was released by E.D. Donnelly of the Alabama Agricultural Experiment Station (Donnelly 1981). This cultivar is low in tannin content and has greater nematode resistance than other sericea lespedeza cultivars.

Vetch Species

The Alabama Agricultural Experiment Station maintained an extensive vetch breeding program when legumes were not popular (Pederson and Knight 1983). Although hairy vetch, Vicia villosa Roth., accounts for 85% of the vetch acreage in the United States, this program emphasized other vetch species and interspecific hybridization (Leffel 1973). In 1959, the Alabama Agricultural Experiment Station released 'Warrior', a variety of common vetch, Vicia sativa L. (Donnelly 1965a). Warrior vetch is resistant to the vetch bruchid and three species of root-knot nematode and produces high forage and seed yields. The Louisiana Seed Company is distributing seed of four proprietary varieties from the Alabama program (Donnelly 1979). These recent releases are 'Vantage', 'Cahaba White', 'Nova II', and 'Vanguard'.

At the Kentucky Agricultural Experiment Station, a locally adapted strain of big-flower vetch, Vicia grandiflora var. kitaibeliana W. Koch, has functioned as a pioneer legume in pasture renovation research conducted by Templeton and Taylor (1975). 'Woodford' has been released as a new variety of big-flower vetch as a result of this work.

Lupine Species

Lupine species under evaluation in Georgia include blue lupine, Lupinus angustifolius L.; white lupine, L. albus L.; and bicolor lupine, L. hispanicus spp. bicolor, Merino, (Pederson and Knight 1983). Lupine improvement objectives include the following: to reduce the alkaloid content, to reduce seed shattering, and to increase winter hardiness. Georgia and Louisiana are involved in lupine improvement. A number of recent cultivar and germplasm releases have been made by John D. Miller, Homer D. Wells, and others of the U.S. Department of Agriculture and the Georgia Agricultural Experiment Station.

The predominant cultivars of blue lupine have been 'Richey', 'Borre', 'Rancher', 'Blanco', and 'Frost'. Blanco and Rancher were released by the Georgia Agricultural Experiment Station and the U.S. Department of Agriculture in 1960 (Forbes et al. 1964, Forbes and Wells 1967). Frost was released by Georgia, Florida, and the U.S. Department of Agriculture in 1970 (Forbes et al. 1970). In 1980, 'Tifblue-78' was released by the Georgia Agricultural Experiment Station and the U.S. Department of Agriculture (Wells et al. 1980a). This cultivar contained more seed-shattering resistance than previous cultivars. Also, Georgia and the U.S. Department of Agriculture released a winter-hardy germplasm, WH-1, of blue lupine in 1980 (Wells and Miller 1981).

Prior to 1980, the predominant cultivar of white lupine was 'Hope', released by the Arkansas Agricultural Experiment Station in 1970 (Offutt 1971). In 1980, the Georgia Agricultural Experiment Station and the U.S. Department of Agriculture released 'Tifwhite-78' white lupine which has a low alkaloid content, improved winter hardiness, and decreased seed shattering (Wells et al. 1980b). In 1982, a bicolor lupine germplasm, Bicolor-1, was released by the Georgia Agricultural Experiment Station and the U.S. Department of Agriculture (Miller and Wells 1983a).

Astragalus Species

Cicer milkvetch, Astragalus cicer L., is a relatively new forage species that shows promise as a grazing or hay crop in the Western United States (Brick and Townsend 1982). This species is under evaluation in several Western States and receives extensive attention in the breeding program in Colorado. Breeding objectives include seedling vigor, improved stand establishment, and drought resistance. Two cultivars have been developed in the United States. In 1970, 'Lutana' was released in Montana and Wyoming; in 1980, 'Monarch' was released in Colorado (Brick and Townsend 1982). Sicklepod vetch, Astragalus falcatus Lam., is also in the improvement programs in the West. While this species is very drought tolerant, it contains toxic compounds that must be dealt with in the improvement program.

Sainfoin

Sainfoin, Onobrychis viciifolia Scop., has received renewed attention in the United States since the 1960's as a result of the threat to alfalfa by the alfalfa weevil, Hypera postica Gyll. An extensive improvement program in Montana has objectives that include increased yields, greater seedling vigor, and improved nodulation. Three cultivars have been developed in the United States. In Montana, 'Eski' and 'Remont' were released in 1964 and 1971, respectively, and 'Renumex' was released in 1977 in New Mexico.

Utah Sweetvetch

Utah sweetvetch, Hedysarium boreale Nutt., is a promising legume in Colorado and other Western States. The breeding program in Colorado is evaluating this species for possible use in oil-shale areas. This attractive native legume is included in legume improvement programs in Utah, and breeding objectives are increased forage and seed yields and improved disease resistance.

Annual Medics

Annual Medicago spp. are included in the legume breeding and improvement program at Logan, UT. Currently, accessions from a recent exploration and collection trip are being evaluated for improved types for western range conditions.

Kura Clover

Kura clover, Trifolium ambiguum Bieb., is included in forage legume improvement programs in Florida, Kentucky, Louisiana, Mississippi, Utah, Texas, and Wisconsin. The development and refinement of the embryo rescue technique by Williams (1978) and

Williams and Verry (1981) have accelerated efforts in interspecific hybridization (Williams and Williams 1983, Collins et al. 1983). Crosses between kura clover and white clover offer the potential for white clover with a more perennial root system, drought tolerance, and disease resistance. Evaluation of T. ambiguum accessions is under way to determine if this species can be used without modification. The U.S. Department of Agriculture's Soil Conservation Service, at Quicksand, KY, has released PI-325489 for use in the temperate regions of the United States. This selection from 120 tested accessions was superior in rhizomatous character, resistance to diseases and insects, and winter hardiness.

Tropical Legumes

In Florida, Kretschmer and Brolmann have an extensive evaluation program involving over 4,000 accessions of tropical legumes representing 12 genera (Pederson and Knight 1983). Genera in the Florida program include Arachis, Aeschynomene, Cajanus, Centrosema, Desmanthus, Desmodium, Indigofera, Leucaena, Macroptilium, Stylosanthes, Vigna, and Zornia. Many of the same species are being evaluated in Louisiana.

Stylosanthes Species

The Stylosanthes breeding and selection program in Fort Pierce, FL, deals primarily with Stylosanthes guianensis (Aubl.) Scv. gracilis humilis H.B.K. and S. hamata (L.) Taub. Both are perennial forage legumes. Two selections of S. guianensis have been successfully grown for years in mixtures with pangola grass, Digitaria decumbens Stent. One selection (IRFL 7035) is very early blooming (August) and sets seeds in September and October. The second selection (IRFL 8201) is a more vigorous stylo that blooms later (mid-October). Seeds from this selection can usually be harvested in December. New stands of both stylos can be obtained in early spring from seed regeneration. Pangola grass is a better companion grass for a good stylograss mixture than is bahiagrass, Paspalum notatum Flugge. Bahiagrass is often too strong a competitor, and most selections of S. guianensis or S. hamata will not survive in a bahia stand for a second year. Several intraspecific S. guianensis hybrids are extremely vigorous and able to perenniate in a mixture with bahiagrass. These hybrids can usually be propagated only vegetatively, since seed production is low and the progeny are heterogeneous.

The search for new S. hamata ecotypes continues on the east coast of Florida, and some new ecotypes have been obtained from the Cocoa Beach-Cape Canaveral area. This area is presently considered the northernmost limit of distribution of S. hamata in Florida. The tetraploid ecotypes of S. hamata (2n=40) are very well adapted to the flatwoods soils. They produce many seeds, the young seedlings establish easily, and the species spreads rapidly. The tetraploid S. hamata has been successfully used to stabilize beach and sand dune erosion. The more common diploid types (2n=20) are less vigorous, with low survival value in grass mixtures.

Arachis Species

Two accessions of Arachis glabrata Benth. and one accession of Arachis benthamii Benth. have been evaluated in the Florida program. The glabrata accessions were 'Florigraze' (PI-421707) and PI-262817; the benthamii was PI-338282. All three were introductions from Brazil. Florigraze is a cooperative release from the University of Florida Institute of Food and Agricultural Science and the Brooksville Plant Materials Center, Soil Conservation Service, U.S. Department of Agriculture. PI-262817 produces higher yields than Florigraze but is more difficult to establish due to coarser rhizomes with fewer nodes per unit of volume. A. benthamii is a stoloniferous species with potential ease of establishment without digging rhizomes. Arachis glabrata (PI-262817) is adapted on droughty soils and produces a hay crop in the spring when moisture in Florida is low. Its advantage in production over Florigraze occurs chiefly in the June cutting, taken just before the summer rainy season.

Although Hawaii does not have a forage legume breeding program, several tropical legumes are used in grazing systems, and evaluation for adaptation is conducted on a number of species. Species emphasized in the introduction and evaluation program are Centrosema spp., Desmodium spp., Neonotonia wightii, and Zornia spp.

Other Legumes

Many other legume species are in evaluation and selection programs in the United States, but the number precludes discussion or even a listing of all of them. For example, in the Southeastern United States alone, a survey conducted in 1983 indicated 76 forage legume species in either breeding or selection programs (Pederson and Knight 1983, 1984). Recent germplasm releases from these programs indicate the diversity of germplasm being evaluated. The Alabama Agricultural Experiment Station is planning germplasm releases of T. purpureum and T. mutabile. The Georgia Agricultural Experiment Station and the U.S. Department of Agriculture have released Tift-1 hyacinth bean, Lablab purpureus (L.) Sweet, germplasm in 1982 (Miller and Wells 1983b) and Tifhardy-1 Desmodium canum (J.F. Gmel.) Schinz and Thell germplasm in 1981 (Miller and Wells 1981). Florida released 'Florida' Desmodium heterocarpon (L.) DC. in 1979 (Kretschmer et al. 1982). The Kentucky Agricultural Experiment Station released KY M-1 zigzag clover (Trifolium medium L.) germplasm in 1982 (Taylor et al. 1982).

The range of diverse legume germplasm available for general and for special purpose use in the United States indicates that the potential exists to maximize forage legumes for energy-efficient animal production. Considering the small number of extensive forage-legume breeding programs in the United States, the large number of species available increases the challenge to breeders to provide the public with improved legume germplasm of the best-adapted species.

Research Needs

1. Develop germplasm of perennial and annual legumes with multiple pest resistance; that is, fungal diseases, virus diseases, insects, and nematodes.

2. Develop new germplasm resources of legume species through tissue culture and interspecific hybridization to incorporate disease resistance and improved rooting characteristics (red and white clovers).

3. Develop nonshattering birdsfoot trefoil with improved disease resistance.

4. Determine allelopathic effects of perennial grass sods of differing ages and growing under climatic stress on establishment and persistence of legumes and their associated Rhizobium strains.

5. Increased research effort to identify more efficient, persistent strains of Rhizobia.

6. Additional multidisciplinary teams to accomplish 1-5 in order to meet current and future needs for more productive legume species.

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Discussion

Easton: You gave a list of important viruses; how was this sorted out?

Knight: Gibson and Barnett took clean material and infected material to the field and followed development of infection and effect on productivity and survival.

Burns: You have disease and pests on top of this of course.

Easton: We have similar pests or diseases in New Zealand but not at the same level of severity, it seems, unless we are underestimating.

Knight: Yes, perhaps you have less extreme environments and stress on the plants. Perhaps the occurrence of a large seed bank in the soil is important.

Brougham: There are major differences between the U.S. and N.Z. environments, especially in summer. Soil pH is also lower in the United States. More winds in New Zealand. Therefore the United States is sure to have more pest problems.

Easton: We have some data to suggest that soil seed levels are not too important in persistency.

Sheath: Does the multitude of difficulties raised by Bill Knight for a range of legumes mean that plants are not quite suited to the environment? Some of the plants appear marginal in performance in the extreme environments.

Knight: This returns to the need for multidisciplinary research approach particularly in relation to pests, diseases, and insects.

Keeney: Despite the listed multidisciplinary team you wish to have, there is still no soil fertility appointment despite the importance registered here about soil fertility in relation to legume growth.

Knight: This is a position identified to be filled as soon as funds permit.

Keeney: Soil fertility people seem to be little involved throughout the United States.

Marten: Minnesota has recently appointed a researcher with soil fertility problems in mind.

Breeding to Improve Temperate Forage Legumes in New Zealand

W. Rumball and H.S. Easton[1]

Abstract

This paper considers the importance of clovers in N.Z. breeding programmes, and shows how past work has led to a range of types adapted particularly to different grazing managements. Most attention has been paid to white clover (*Trifolium repens*) but some major weaknesses in the species still remain. These include its need for large amounts of single superphosphate, its tendency to cause bloat, and its susceptibility to pests. Red clover (*Trifolium pratense*) is the second most important legume in N.Z. pastures, and breeding programmes have concentrated on improving its persistence, particularly through disease resistance. For both white and red clovers, breeding objectives overseas are largely similar to our own. The greatest disparity between N.Z. and overseas breeders appears to be in the species and genera used to fill minor or localised roles.

Introduction

This paper summarises past targets, progress, successes, and failures in the breeding of temperate legumes in New Zealand. It then discusses what current or new targets are being set and might reasonably be achieved. Within this framework, white clover (*Trifolium repens* L.) will be used as the major example, because of our in-depth experience with this species in New Zealand. White clover breeding in other countries will be discussed where needed, to compare or contrast with our own, but there is no attempt to provide a complete world coverage.

The paper also discusses other important pasture legumes in New Zealand and considers overseas work. Once again, the main effort is to draw out general themes, rather than a complete coverage of programmes. Legume species which may be used overseas, but are unfamiliar in New Zealand, receive little attention.

Past Breeding

White Clover

It is ironic that such countries as New Zealand and Australia, where pasture legumes have been given great importance, have virtually no suitable native legumes. The history of pasture legumes, and of their breeding, is largely that of their adaptation to the diverse environments and management systems found here.

White clover is the dominant pasture legume in New Zealand. Along with the attributes common to all legumes, it has the following extra advantages for temperate pastures.

1. Large genetic variation within populations and environments, ensuring the filling of diverse micro-environments present in a pasture.

2. Stoloniferous habit enabling survival and vegetative spread.

3. Abundant seeding, even under grazing, creating a reserve of hard seed, which ensures regeneration after drought or severe pest attack.

4. Seasonal rhythm, which in most environments is dominated by warm-season growth that complements the seasonal production pattern of ryegrasses.

5. Indeterminate growth habit, which confers more stable nutritive quality and less restrictive management constraints than those shown by species which reach a distinct stage of maturity or which are slow to recover from grazing.

This list of attributes places white clover in virtually all N.Z. seed mixtures, where it is effectively regarded as a permanent maintainer of seasonal growth, high quality forage, and a source of nitrogen to itself and grass associates.

White clover breeding began in New Zealand in the 1920's with assessment of the wide range of material traded here and identification of those lines showing satisfactory growth, persistence and adaptation to grazing in the environments of our major pastoral regions. Leafy, vigorous, competitive plants from long-term pastures became the basis of a synthetic cultivar, subsequently called 'Grasslands Huia', that was well adapted to the moist lowland areas of New Zealand.

Huia remained the only recognised white clover cultivar in New Zealand for 40 years. In the last 10 years, two cultivars have been released for special purposes. Pitau was bred for better cool-season growth by crossing Huia stock with Mediterranean material, and Tahora was bred for persistence and growth in moist hill country, by selecting within a large collection taken from the moister North Island hills. Pitau is more erect and open than Huia, while Tahora is more prostrate and dense, making them more suitable for cow and sheep grazing respectively.

The Grasslands' range of white clover types is not unique. The Welsh Plant Breeding station pioneered a similar range of types and has similarly used both wild U.K. collections and Mediterranean introductions to provide this range. The Welsh have paid particular attention to stature, in an effort to breed clovers that will not be smothered by grasses when the traditionally high levels of artificial nitrogen are applied. The Welsh breeders also desired that the new clovers continue to fix their own nitrogen under these same conditions and so have attempted to locate strains of rhizobia that are active in high-nitrogen surroundings and are compatible with the vigorous but open types of clover. The main difference between Grasslands and the Welsh Plant Breeding Station is, therefore, their greater problem in obtaining high seed yields reliably. In the United States, 'Star' white clover

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has been bred as a prolific seeder, and Australia has made use of free-seeding ecotypes. Some Southern States of the United States have also released cultivars of the tall, short-lived ladino types for cool-season growth.

Red clover

Work with red clover (Trifolium pratense) has had a similar history in New Zealand, except that it has been dominated by a search for greater persistence, and marked by the use of artificial tetraploidy. Early and late flowering cultivars have been released and Mediterranean material has contributed better cool-season growth. Artificial tetraploidy has been a useful approach, although seed production becomes more difficult because of inadequate pollination, particularly for the earlier types.

Overseas, Scandinavian breeders led the emphasis on improving persistence in red clover, particularly through the use of tetraploidy and disease resistance. West Australian breeders have been more concerned with sheep infertility problems caused by high levels of formononetin, and have successfully bred two low-level cultivars.

Other Legumes

Of the other forage legumes, Lotus pedunculatus has received most breeding attention in New Zealand. Artificial tetraploidy and crossing to Mediterranean introductions were both employed, and 'Grasslands Maku' was released in 1972. It is for use in soils too acid, moist or low in phosphate for red and white clovers. The species as a whole has only been used significantly in New Zealand and, indeed, has only been researched widely since Maku's release. Although it is bred to fill a niche to which white clover is ill-adapted, the various shortcomings of Maku relative to white clover have been highlighted by critics, notably its slow establishment and slow recovery from grazing. Its resistance to grass grub and non-bloating properties prompted its trial in high fertility swards, but here failure to compete with ryegrass was evident.

Other species and genera of legume have dominated plant breeding efforts in some areas of the world. These include the annual Trifolium species in the Southern United States; winter-dormant species such as T. ambiguum and T. hybridum in colder regions of Australia and Canada; and drought-tolerant species such as sainfoin (Onobrychis viciifolia) in Eastern Europe and the U.S.S.R. In New Zealand we have begun screening large collections of diverse clover and other legume species in the hope of locating perennial or annual lines more suited to regions of severe drought, infertility, cold, etc. The drought regions have involved us in screening forage shrubs such as honeylocust (Gleditsia triacanthos) and tree lucerne (Chamaecytisus palmensis), but we are less advanced in this field of forage trees than are researchers in more arid countries.

Perspective on Past Work

A study of the major results shows two general points.

1. The apparent array of diverse genera being studied in countries such as New Zealand and the United States conceals the fact that by far the greatest emphasis goes on single species; white clover in New Zealand and Wales, and lucerne in the United States. This concentration makes it vital that efforts are made to maximise the range of genetic variation available. The Welsh Plant Breeding Station has made 17 collecting expeditions since 1961 and thereby added 326 new populations of white clover to its stored stocks. The current new techniques of somaclonal culturing are also attempting to increase the range of genetic variation available, but it is not yet clear what 'new' characters might be obtained, nor their performance.

2. Despite the proximity to plant breeders of other disciplines such as plant physiology, animal nutrition, and chemistry, the vast majority of new legume cultivars have been released following selection programmes based on yield, persistence, and pest resistance--that is, characters easily measured or directly related to animal intake.

Current And Future Emphases

1. Regional Breeding

   Surveying the present situation with white clover breeding, we note that we have succeeded in improving cool season growth and in establishing some grazing adaptation. Our cultivars are well adapted to our own conditions and should also be extensively traded around the world. However, none of the three N.Z. cultivars performs well in dry regions. They cease growth or are overgrazed early in a drought and may not even be able to mature seed beforehand. Farmers in such regions often use sub. clover (T. subterraneum) instead. Nevertheless, there are many farms in dry regions where white clover was sown many years ago and where remnants remain. Grasslands breeders have collected samples of this surviving material in recent years, with the aim of searching for adapted ecotypes. Other regional breeding programmes underway are based in Northland and Southland, each programme involving both imported and locally collected material. The Northland programme has identified eelworm resistance as an important cultivar requirement, and a selection bred from Pitau for tolerance to stem eelworm (Ditylenchus dipsacii) has performed well there.

2. Root Structure and Phosphate Use

   A major theme in Grasslands Division's research has been the use of phosphate by white clover. From a breeder's viewpoint, the aim has been to learn which features of a plant will allow it to survive and grow well in low-phosphate soils. At this stage it is not clear whether a breeder should attempt to improve a plant's ability to forage for phosphate, by means of a better root system, or its ability to retain phosphate in organs, such as stolons, below grazing height.

It is possible that a change in type of root system might also improve a plant's ability to survive drought and attacks by root-eating insects such as the native grass grub (Costelytra zealandica).

3. Pests

Data are coming to hand on the damage done to white clover by insects, diseases, nematodes and viruses, which will allow the resultant economic loss to N.Z. farming to be estimated. Following advice from colleagues in these research fields, breeders are working towards tolerance or resistance to such pests. We are attempting to devise suitable screening procedures and to breed improved populations.

Grass grub is particularly destructive, but we have so far been unable to identify resistant populations nor, indeed, even to identify which plant characters should be used for selection. Our colleagues have identified chemicals in Lotus pedunculatus that have toxic or deterrent effects on grass grub, but these chemicals are not at realistic levels for selection in white clover.

4. Bloat

This is regarded as the main nutritional problem for white and red clovers. Grasslands breeders have accepted other DSIR research findings that showed non-bloating legumes to be mainly those species that contained condensed tannins in their leaves. We have screened thousands of white clover plants for such leaf tannins but without success. Canadian work, which aims to breed bloat-safe lucerne by selecting for a slower rate of cell rupture, is being followed with interest. It is hoped there will not be a simultaneous reduction in the rate of food intake and therefore also of animal growth rates.

We have spent a lot of time and effort for no tangible return in three areas--bloat, grass grub, and phosphate efficiency. These remain major challenges to white clover breeding in New Zealand. We can claim to have put effort and imagination into all three areas but cannot discontinue our interest because of failure. New material and new approaches will be tried. Our commitment to these objectives is shown by our attempts to reach them by interspecific hybridisation of clovers. Over a number of years, we have worked intermittently on production of hybrids between Trifolium species. The condensed tannins of T. arvense, the tap root system of T. uniflorum, and the virus resistance of T. ambiguum would all be valuable traits to bring into the T. repens genetic pool. Progress has been made with embryo culture techniques and we do have a few hybrid plants. However, they have not contributed to our plant breeding programmes so far, and we foresee several years of laborious backcrossing and agronomic testing before any commercial success is likely. A more promising approach may be through somatic hybridisation and tissue culture, for the forage legumes appear reasonably amenable to such work. As well as directly generating variability within species, such techniques may help realise the potential of interspecific hybridisation work: firstly, in producing greater numbers of hybrids; secondly, through somacloning, exposing the variability within the hybrid genome; and thirdly, in allowing partial gene exchange.

5. Nitrogen Fixation

We are aware of concern about the failure of pasture legumes to maintain nitrogen fixation at high soil N levels. This is not only pertinent where fertiliser nitrogen is applied but also relates to the self-limiting nature of pastures relying on fixed nitrogen. Fixation drops off at nitrogen levels which are still limiting for grass growth, and under high levels of utilisation, soil total N levels may be falling. A colleague at Lincoln has been surveying white clover for variation in response in N fixation to soil N levels.

6. Persistence and Forage Quality For Red Clover

Future emphasis with red clover is likely to be a continued search for improved persistence. This dominates our programme to the extent that most breeding material now passes through the 'pest nursery'; a block of land where diseases, viruses, eelworms, etc. have been allowed to build up by continuous red clover plantings. We are also following an overseas lead in trying to reduce the level of formononetin in some selections. In New Zealand, it has become evident that special attention must be given to retaining agronomic type during selection of low formononetin plants, or the population will become more open, sparse, and early flowering.

7. Other Legumes

The other species and genera will continue to be used in New Zealand in problem niches that cannot foreseeably be filled by white and red clovers. It will remain vital that we continue to encourage the collection and screening of new and diverse gene pools.

Concluding Remarks

With the above in mind, we can foresee a continued trend to special cultivars, for regions and for management systems. Pest and disease resistance will be increasingly sought as the real significance of particular scourges is established. New technology may enable better use to be made of interspecific hybrids so that more radical and perhaps more rapid responses can be made as new requirements are perceived. For the major species, breeding should in most cases be able to keep pace with expanding knowledge of the ecology, physiology and feed quality of these plants.

It can be seen that legume breeding in New Zealand has passed through several stages. The first was that of identifying and then improving clovers which were reasonably adapted to the range of environments and managements over the country as a whole. The

second stage was one of specialised breeding targets for particular regions or characters, such as disease resistance, dairy-cow grazing, hill country, etc. The third stage must deal with the much more difficult problems that have so far not been solved--bloat, phosphate economy, etc. Sometimes these are problems because we lack the information on what to select, while in other cases we simply lack the variants we need. This is the basic reason we continue the search for new plant collections, attempt difficult hybridisations, and support the attempts of our genetical colleagues to produce new plant types by somacloning, mutagenesis, and other new techniques.

Research Needs

1. There is a major need for stable legumes in the dry regions of New Zealand and the South-eastern United States. If this is to be resolved using annual species, the breeding target will be toward cultivars that seed and re-establish reliably, despite fairly intensive grazing.

2. Ecological studies are required on plant history in the sward. Is reseeding an important element of white clover persistence?

3. More knowledge is needed on traits affecting competition with grasses. For instance, why are clover levels in hill pastures so low?

4. Research into bloat should be scaled up, as this problem is a major disincentive to using legumes to their fullest capacity.

5. Breeding for persistence should be maintained in all legumes. To a large extent this means breeding against the appropriate pests, e.g., crown rots in red clover, grass grub in white clover, and aphids etc. in lucerne.

6. More studies are needed on the significance of diseases, and on their relative importance and interactions among them.

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Discussion

Lancashire: The speaker mentioned selection for herbicide tolerance. This could be very significant for seed-production problems. In seed-producing areas, buried seed loads are enormous, and much of this is hard seed. This makes it very difficult to produce pure seed of new cultivars.

Minson: Do you consider that clear nutritive requirements have not been defined for legumes? In Queensland, we require breeding just for more protein content.

Rumball: We see introducing condensed tannins through gene transfer from related *Trifolium* species into white clover as a priority, to remove bloat.

Barry: For N.Z. temperate forages of high DM digestibility and nitrogen content, I feel our nutritional objectives are simple and clear. These are (1) to introduce condensed tannins into white clover both to eliminate bloat and to increase amino acid supply and (2) to decrease shear strength in perennial ryegrass to produce cultivars that will have a faster rate of throughput in the rumen and hence greater potential for voluntary intake.

Rumball: We agree on (1) but ruminant nutritionists are divided on (2) over whether there is enough information to ask plant breeders confidently to select on this basis.

Syers: You mentioned selection of clovers to modify root systems for better phosphate foraging. Why not select for low tissue phosphorus?

Rumball: We have a breeder currently overseas investigating a wide range of phosphate parameters in nutrition of white clover. We hope that he will return with some breeding objectives sorted out.

Breeding to Improve Subterranean Clover in Australia

W.J. Collins and J.S. Gladstones[1]

Abstract

Although subterranean clover is widely used as a pasture legume in southern Australia and to a lesser extent in New Zealand, the United States and parts of the Mediterranean region, it has long been recognized as having shortcomings which limit its contribution to pasture improvement. The major efforts to improve subterranean clover have come from programmes in Australia. Initially, cultivars were selected from naturalized strains, but with the establishment of the National Subterranean Clover Improvement Programme (NSCIP), breeding and deliberate introduction from native Mediterranean populations became increasingly important. This paper outlines the operation and breeding objectives of the NSCIP before reviewing the selection criteria and evaluation methods currently in use. The NSCIP has been responsible for the development of several new cultivars which combine low oestrogenic activity with improved adaptation. Considerable potential exists for increasing subterranean clover's contribution to agriculture through a continuing programme of genetic improvement.

Introduction

Subterranean clover (Trifolium subterraneum L.) is a winter-growing, self-pollinating annual, which is naturally distributed mainly around the Mediterranean region and parts of Western Europe (Katznelson and Morley 1965). Its deliberate use as a pasture legume began in southern Australia over 80 years ago, following accidental introduction some years earlier, and since that time it has been sown on an estimated area of 16 million ha (Donald 1970). Together with the use of superphosphate and trace elements, subterranean clover has been a key factor in the improvement of soil fertility in cereal and mixed farming districts, and both livestock and crop production have increased dramatically where it has been grown (Underwood 1951, Underwood and Gladstones 1979). Although the net financial benefits of subterranean clover to Australia are difficult to estimate exactly, its value in terms of soil nitrogen accumulation alone may be of the order of $A400 million annually (assuming a nitrogen accumulation rate of 40 kg N/ha/yr (Watson 1963)).

Subterranean clover has also been introduced into a number of other countries, in most cases by way of Australia. Nowhere is it grown on the same scale as in Australia, but nevertheless in countries such as New Zealand (Saxby 1956) and the United States (Knight et al. 1982), it plays a valuable role in pasture improvement. Other countries in which it has grown successfully include South Africa, Argentina, Chile, Uruguay, Japan, and, at higher altitudes, Kenya and Venezuela. Subterranean clover also has considerable agronomic value in its native habitat in the Mediterranean region (Katznelson 1974). As well as contributing to the natural vegetation, it has been sown on some 80,000 ha, mainly in Spain and Portugal.

Despite its clearly established value, subterranean clover has long been recognized as having some shortcomings which prevent it from making its full potential contribution. Many of the older cultivars were not well enough adapted to their environments and management systems. In addition, several were found to contain high levels of the oestrogenic isoflavone formononetin, which in some parts of Australia has resulted in severe infertility in sheep.

The major efforts in subterranean clover improvement have come from programmes in Australia, a fact which is perhaps not surprising in view of the vital role played by the species in that country's agriculture. Although the present paper is based mainly on the Australian programmes, mention should be made of other programmes endeavouring to improve subterranean clover. In the Mediterranean region, researchers in Portugal (Crespo 1970), Spain (C. Gomez Pitera, personal communication; A. Ramos Monreal 1978), Italy (E. Piano, personal communication) and Tunisia (Jaritz 1982), in addition to testing Australian cultivars, are also examining the possibility of selecting superior cultivars from locally occurring strains. In the United States, there are programmes in Florida, Georgia, Mississippi and Texas aimed at developing better adapted and more productive cultivars through plant introduction and evaluation (Knight et al. 1982).

History of Subterranean Clover Improvement in Australia

There are currently 22 registered cultivars of subterranean clover in Australia (see table 1), covering a broad maturity range and including representatives from each of the three recognized subspecies. (Pending satisfactory resolution of the taxonomy of T. subterraneum, we have retained the subspecies rank (Katznelson and Morley 1965) rather than re-defining them as species as proposed by Katznelson (1974)). In addition, a further four crossbred lines are under consideration for release. Some cultivars are no longer recommended for use either because they have been superseded or because of shortcomings which became known subsequent to commercialization.

As table 1 shows, most of the cultivars released so far have been developed from naturalized strains found in southern Australia. In fact, until the early 1960's this was the sole method of improvement in subterranean clover. Initially there were no organised programmes; strains were selected by farmers and agronomists, largely on the basis of differences in maturity, to provide cultivars for a range of broad ecological niches. It is only within the last 30 to 40 years that formal improvement programmes have been established, utilising breeding

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Table 1 - Origins and some characteristics of Australian subterranean clover cultivars[1]

Cultivar	Subspecies[2]	Origin	Date Commercialized	Maturity[3]	Oestrogenic Activity
Mt. Barker	S	Naturalized, Mt. Barker, S. Australia	1906	137	Low
Dwalganup	S	Naturalized, Boyup Brook, W. Australia	1929	83	Very high
Tallarook	S	Naturalized, Tallarook, Victoria	1935	163	High
Bacchus Marsh	S	Naturalized, Myrniong, Victoria	1937	131	Low
Yarloop	Y	Naturalized, Yarloop, W. Australia	1939	109	Very high
Clare	B	Naturalized, Clare, S. Australia	1950	129	Low
Geraldton	S	Naturalized, Moonyoonka, W. Australia	1958	97	High
Woogenellup	S	Naturalized, Elgin, W. Australia	1959	130	Low
Nangeela	S	Naturalized, Nangeela, Victoria	1961	143	Low
Dinninup	S	Naturalized, Boyup Brook, W. Australia	1962	113	Very high
Howard	S	Bred (Tallarook x Northam), Canberra	1964	Variable, 93-135	High
Daliak	S	Naturalized, York, W. Australia	1967	97	Low
Seaton Park[4]	S	Naturalized, Seaton, S. Australia	1967	110	Low
Uniwager	S	Artificial mutant of cv. Geraldton, W. Australia	1967	103	Low
Trikkala	Y	Bred (Larisa x Neuchatel[5]), W. Australia	1976	112	Low
Larissa	Y	Introduction (CPI 39313Y[6]), Larissa, Greece	1977	142	Low
Nungarin	S	Bred (Northam A_2 x Daglish[8]), W. Australia	1977	77	Low
Northam	S	Naturalized, Northam, W. Australia	1977[9]	78	Low
Esperance	S	Bred (Daliak x Bacchus Marsh), W. Australia	1978	120	Low to mod.

Table 1 - Origins and some characteristics of Australian subterraneum clover cultivars--continued[1]

Cultivar	Subspecies[2]	Origin	Date Commercialized	Maturity[3]	Oestrogenic Activity
Meteora	Y	Introduction (CPI 39327YB), Larissa, Greece	1981	148	Moderate
Enfield	S	Naturalized, Kilmore, Victoria	1984	118	Low to mod.
Dalkeith	S	Naturalized, Dalkeith, W. Australia	1985	98	Low

[1]Listed in order of commercialization.
[2]S, ssp. subterraneum; Y, ssp. yanninicum; B, ssp. brachycalycinum.
[3]Days from sowing to flowering, for early May sowing at Perth, W. Australia.
[4]The Seaton Park cultivar has been found to differ slightly but clearly in several characters from the original strain found in South Australia (Rossiter et al., unpublished data).
[5]Early flowering natural mutant of Yarloop.
[6]CPI, Commonwealth Plant Introduction number.
[7]Natural variant of Northam.
[8]Naturalized, Daglish, W. Australia.
[9]Some seed commercially available 1968.

and also deliberate introduction from native Mediterranean populations in the development of new cultivars.

Breeding of subterranean clover was first attempted in Australia in the 1930's and 1940's (Donald and Neal-Smith 1937, Loftus Hills 1944), but no cultivars were produced. Two subsequent programmes have been more successful. One, which is no longer in operation, was based at the Commonwealth Scientific and Industrial Research Organization (CSIRO), Canberra, and the other is located jointly at the Institute of Agriculture, University of Western Australia and the Western Australian Department of Agriculture. The Canberra programme commenced in 1954 (Hutton and Peak 1954) and produced the clover stunt virus resistant cultivar Howard (Peak and Morley 1963). Howard was selected from a cross between Tallarook and Northam and was the first bred subterranean clover cultivar.
1The Western Australian programme began at the University of Western Australia in 1950 with the aim of producing cultivars for the wheatbelt of that State (Millington 1960). It was reorganised in 1967 (University of Western Australia 1967, Francis et al. 1970) on a joint basis between the University and the Western Australian Department of Agriculture with some input by the CSIRO which has since ceased. From 1970 onwards there was increasing participation by Departments of Agriculture in other States, and the programme expanded into what is now known as the National Subterranean Clover Improvement Programme (NSCIP) (Stern et al. 1983). There is also a small programme currently operating independently within the Victorian Department of Agriculture. Cultivars released from the NSCIP (in order of release) are Geraldton, Uniwager, Trikkala, Larisa, Nungarin, Esperance, Meteora and Dalkeith. The morphological and agronomic characteristics of these and the other registered cultivars have been described by Collins et al. (1984).

The National Subterranean Clover Improvement Programme

Organisation

Until recently, the NSCIP has operated on a relatively informal scientist-to-scientist basis. However, with the increase in interstate involvement in both field testing and the definition of breeding aims, a more formalized structure became necessary. The newly adopted arrangement (Gladstones 1983) ensures that groups of material, including both crossbred and naturally-occurring lines, selected as being suitable for testing in particular ecological ranges, are assembled and made available to all collaborators simultaneously. A projected timetable indicating when particular groups will be distributed is aimed at providing collaborating bodies with adequate notice to organise their field-testing programmes.

For all groups, the selection and testing procedures can be divided into two broad phases:

Phase 1: Pedigree Selection in Segregating Generations. This covers an eight-year period, from the initial crossings to the final selection and row-bulking of pure lines and is mainly conducted in Western Australia.

Phase 2: Field Testing of Pure Lines. This is conducted in three stages, all of which are Australia-wide.

Stage 1: Initial Screening (1 year)

Small quantities of seed (about 10 g per line) are supplied to each collaborating State for micro-plot observations. Field or glasshouse screening may also be conducted for disease and pest resistance or for other characteristics

considered locally important, for which screening is not feasible in Western Australia.

Stage 2: Small-Scale Plot Testing (3 Years, Continuing)

Seed of the better lines from stage 1 is supplied to collaborators in quantities of about 100 g per line for plot testing under common grazing in two or more environments in each State.

Stage 3: Larger-Scale Field Testing (Long-Term)

About 1 kg of seed of the best lines from stage 2 is supplied to each State for field testing similar to that of stage 2, but in more environments and usually in larger plots.

Pure seed increase of promising lines for commercial release may begin after stage 2 or during stage 3 testing, depending on the degree of promise of individual lines and the perceived need for them in agriculture.

Sources of Genetic Variability

Three sources of variability are currently being utilised in the NSCIP:

1. Strains naturalized in Australia.

2. Mediterranean introductions.

3. Crosses among selected lines.

Chemically induced mutations were also used in an earlier phase of the programme. A low-oestrogen mutant of Geraldton derived in this way (Francis and Millington 1965a) was released as cv. Uniwager. However, because of low herbage production, it had only limited commercial success.

A major collection of germplasm is maintained in conjunction with the NSCIP. Details of its development and utilization have been described by Francis and Gladstones (1983). Currently there are over 6000 lines in the collection, of which about 300 were collected in Australia and the rest overseas. Locally occurring strains have already figured prominently in cultivar development, and they continue to play a valuable role both directly and indirectly, through crossing, in the NSCIP. The variability within subterranean clover in Australia has not yet been fully explored, and there is scope for further collecting (Gladstones and Collins 1983).

Breeding Objectives

The breeding objectives of the NSCIP have been discussed in several papers in recent years (Francis et al. 1970, 1976, Underwood and Gladstones 1979, Stern et al. 1983, Francis and Gladstones 1983) and the present aims are summarized below for the groups defined by Gladstones (1983) in the recent reorganisation of the programme. In all groups, low oestrogenic activity is an essential requirement.

Group 1. Subspecies Subterraneum--Early Maturity, Range Approximately cv. Nungarin to cv. Daliak or Slightly Later. The main requirement in this group is for cultivars which can persist in wheatbelt areas of medium to low rainfall and regenerate successfully after frequent cereal cropping. Disease problems are minimal.

The principal aims are to improve seed production, burr burial, hard-seededness, and, if possible, the capacity to survive and produce seed during periods of intermittent moisture stress in spring. The last is considered to be a particularly important objective for eastern Australia, where the end of the growing season is poorly defined. Earliness per se is considered more important in northern and central parts of the dry Western Australian wheatbelt, where the growing season is short and relatively well defined.

Group 2. Subspecies Subterraneum and Yanninicum--Early Midseason Maturity, Range Approximately cv. Seaton Park to cv. Woogenellup. Cultivars required in this maturity range are primarily for mixed farming, medium to high rainfall areas, where cropping is significant and where disease problems, particularly in the later end of the maturity range, can be very important.

Esperance was the first cultivar selected specifically for resistance to clover scorch (caused by the fungus *Kabatiella caulivora*, and several promising crossbreeds of Woogenellup maturity with good tolerance of clover scorch and root rots (*Pythium* and *Fusarium* species) are currently under consideration for release. More recently, the main attention has shifted to the earlier part of this maturity range (around cv. Seaton Park) where the objectives are to combine resistance to clover scorch with good seed production and relatively high levels of hard-seededness. Resistance to blue-green aphid (*Acyrthosiphon kondoi*) is also given some emphasis.

The subspecies *yanninicum*, with its specific adaptation to soils prone to waterlogging, plays an important role in medium- and high-rainfall districts. Following the releases of Trikkala (early midseason maturity) and Larisa and Meteora (late), the emphasis is now on developing cultivars of intermediate maturity, having good resistance to clover scorch and improved levels of hard-seededness. (Part of this work is being conducted in South Australia by Dr. P.E. Beale).

Group 3. Subspecies Subterraneum and Yanninicum--Late Midseason to Late Maturity, Range Approximately cv. Mt. Barker to cv. Tallarook. Cultivars in this group are for use in semi-permanent or permanent pastures in high-rainfall areas. Since the early 1970's, resistance to diseases and insect pests has become of paramount importance in this maturity range. At present, the main objective is to develop cultivars which have adequate resistance to clover scorch, root rots, blue-green aphid and red-legged earth mite (*Halotydeus destructor*). Resistance to other fungal foliage diseases (Barbetti 1983) will be sought if these become important. Hard-seededness has not been established as being important and is not emphasized.

Group 4. Subspecies Brachycalycinum. Members of this subspecies are adapted to neutral or slightly alkaline soils. The principal objective is to develop cultivars which are earlier flowering and have higher levels of hard-seededness than the one existing Australian cultivar, Clare (early midseason maturity). This should extend the range of the subspecies into lower rainfall cropping areas where good regeneration is an especially important attribute.

No breeding has been carried out in this group so far. Work is limited to the preliminary screening of Mediterranean introductions which are then supplied to Dr. P.E. Beale (South Australian Department of Agriculture) for the main initial field testing.

Selection Criteria in Breeding

Several of the criteria that are used in the NSCIP have been discussed previously by Francis et al. (1970, 1976) and Gladstones (1975), and details of some of the selection procedures have been described by Nicholas and Gillespie (1983).

Early Generation Selection. Parent and early generation selection is currently based on the following criteria:

Maturity

This includes time of commencement of flowering, duration of flowering, and rapidity of seed development. Selection for time of flowering is made only within broad limits because of the diversity of environments which must be catered for and because of a lack of knowledge of optimum flowering time for most environments.

Rapid flowering and seed development are selected for only in the very early maturity range, as essential components of earliness. In other maturities, equal emphasis is now given to selecting alternative types which flower and produce seed over a longer period with the expectation that seed production in such types will be less vulnerable to periods of intermittent moisture stress in spring (Andrews et al. 1977). Further research is needed to determine the optimum rapidities of flowering and seed development for different environments.

Oestrogenic Isoflavone Content

Although infertility problems in sheep caused through grazing of oestrogenic subterranean clover pastures appear to have declined in severity in recent years, they are still of considerable economic significance.

The main selection is for low formononetin (the chief oestrogenic isoflavone), using a thin layer chromatographic screening technique developed by Francis and Millington (1965b). A maximum level of 0.2% of the leaf dry weight is used as a guide, but levels of 0.1% or lower are preferred. It is still not known how low a level is needed before all adverse effects are eliminated.

In later generation, homozygous rows, the isoflavones genistein and biochanin A are also assayed. Although their role in the oestrogenicity problem has been shown to be minor, lines with low total isoflavones are kept wherever possible.

Burr Burial

Although there is less accent than formerly on high seed production per se in early generation selection, major emphasis is still placed on strong burr burial which is an important determinant of seed yield (Collins et al. 1976). In addition to increasing seed production, good burr burial is important for pasture regeneration. Buried seeds are protected to some extent from grazing animals and fire, and they also establish more successfully than surface seeds (Hagon 1974).

Good burr burial (in rows and spaced plants) is usually associated with peduncles that are perpendicular, or nearly so, to the soil surface.

Seed Impermeability or Hard-Seededness

This is the most important germination-regulation mechanism in subterranean clover and is a prime determinant of its long-term persistence (Gladstones 1967, Quinlivan 1971). Hard-seededness prevents seed loss through precocious germination in areas which have erratic summer rainfall, and it provides a seed reserve in the soil for pasture regeneration following years of cropping or drought. The requirement for hard-seededness in subterranean clover depends on both the environment and the frequency of cropping and the duration of cropping cycles. Although optimum levels of hard-seededness have not, as yet, been defined, field experience indicates that the levels in many of the existing cultivars are lower than desirable.

In the early group (Nungarin to Daliak maturity), destined for areas of high cropping intensity, selection is aimed at increasing hard-seededness substantially. Selection for enhanced hard-seededness is also applied, though less rigorously, to the group for medium- to high-rainfall cropping environments (Seaton Park to Woogenellup maturity). No selection for hard-seededness is imposed in the late group (Mt. Barker to Tallarook maturity).

Seed Dormancy

The importance of dormancy in preventing premature germination of permeable (or soft) seed in the field is unclear (Quinlivan 1971, Taylor 1972). Although selection for seed dormancy was part of an earlier phase of the programme (Francis et al. 1970) there is no regular screening for this character at present. However, many of the recent crosses made on the programme have been planned deliberately to have at least one parent with a high level of seed dormancy.

Disease Resistance

This has become increasingly important as improved pastures have aged. The major emphasis is on resistance to clover scorch, particularly in the late maturity group and to a slightly lesser extent in the early midseason group. Screening of crossbred lines as well as naturalized and overseas strains is done in the field in Western Australia (Gillespie 1983). Resistance to root rots is also tested in the field in Western Australia (Gillespie 1983) but on a more limited scale; at present, only lines which have shown good resistance to clover scorch are included. Limited screening for resistance to subterranean clover red leaf and stunt viruses has been conducted by the Tasmanian Department of Agriculture (G.R. Johnstone, personal communication) in search of suitable parental lines for future breeding.

Resistance to Insect Pests

Screening for resistance to blue-green aphids, using controlled environment conditions, commenced in Western Australia in 1980 (Gillespie 1983). So far it has been restricted to advanced crossbreds and some promising naturalized and introduced lines. There has also been some screening for resistance to red-legged earth mites, but so far it has not been possible to incorporate this as a regular part of the programme.

Marker Characteristics

Selection for distinctive and unique marker combinations, based mainly on leaf marks and calyx and stipule pigmentation, has been necessary because current seed certification schemes require that cultivars be easily and reliably distinguished in the field. However, alternative methods of certification and of strain distinction are under consideration.

Later Generation Selection. Final evaluation of selected lines is conducted in the field using swards subjected to appropriate systems of common grazing and cropping. Seed production, seedling regeneration and the build-up of seed reserves in the soil, all factors in persistence, are important selection criteria early in field testing, and herbage production may also be considered. Observations are also made on burr burial, hard-seededness, and reaction to soil type, diseases and insects. A further consideration in the longer term is the performance of potential cultivars in mixtures amongst themselves and with the commercial cultivars they are designed to replace. Long-term persistence as a dense, dominant stand is regarded as the ultimate criterion of field success.

In a herbage plant improvement programme such as this, the lack of emphasis on selection for herbage production per se may seem anomalous. The rationale for this approach has been discussed at some length by Gladstones (1975, 1980a). Subterranean clover is normally part of a mixed sward where its contribution, through nitrogen fixation, influences the productivity of the whole sward and that of subsequent crops. By selecting for better adaptation (through improvement of seed production, hard-seededness, and disease resistance) it is argued that subterranean clover will become more prominent in the sward and in this way make a greater contribution to overall productivity than the gains (probably small) achievable through selecting specifically for clover herbage yield. Even under monoculture conditions, improved adaptation is likely to increase winter herbage production since this is largely dependent on seedling density at the break of the season (Donald 1954).

Evaluation Methods

As yet, the determinants of agronomic success of subterranean clover in the field are not fully understood, although a number of important characteristics have been identified (Rossiter 1966, 1977). For this reason, extensive and prolonged field testing is crucial in the development of new cultivars. We believe that it is sufficient to grow promising lines in mixtures and pure cultures under common grazing, and cropping if relevant, and select the latest maturing strain(s) which persist(s) and compete(s) well in a given environment. Testing in a wide range of environments is considered more important than attaining high statistical accuracy in any one environment.

Grazing trials to assess animal production are not recommended as part of the evaluation procedures prior to commercial release (Gladstones 1975, 1980a, 1983). Objections to their use arise from the high cost and difficulty of running such trials which restricts the number of sites that can be used and the number of genotypes tested. These are serious impediments to a programme which seeks cultivars adapted to a wide variety of conditions. Also, the selection of genotypes on other bases necessary to reduce the numbers would, if done properly, decrease the likelihood of worthwhile differences being detected under grazing.

In the current programme it is recommended that animal production measurements should only be made as part of the final characterisation of new commercial cultivars. They are justified only after a cultivar has adequately demonstrated its agronomic success under commercial conditions, and when enough is known about it to define the most appropriate location(s) for grazing trials and the most appropriate treatments and controls for comparison. Otherwise the hard-won results are in danger of being misleading.

Future Improvement in Subterranean Clover

The use of subterranean clover as the basis of a system of productive and sustainable agriculture, embracing both cropping and livestock production, will undoubtedly continue in the foreseeable future. It is now attracting greater interest than in recent years because of the energy crisis and the resultant high prices of nitrogen fertilizers (Gladstones 1980b).

Considerable potential exists for increasing subterranean clover's contribution to agriculture.

This may occur, firstly, through expanding its use into new areas. Australia (Morley 1961), the United States (Knight et al. 1982) and the Mediterranean (Pire Solis 1964, Katznelson 1974) each have several million hectares of grassland to which it would be theoretically suited. Secondly, its performance might be improved in existing areas. The extent to which this potential can be realised will depend, in no small way, on continuing genetic improvement.

What are the long-term prospects for improvement? As Gladstones (1980a) has stressed, the early products from the organised subterranean clover improvement programmes are by no means the ultimate in pasture plants, and further improvement can be confidently expected. Breeding objectives, however, will become more complex, and continued progress will be dependent on increased resources for clover breeding. Supporting research will also be required to further elucidate the factors contributing to adaptation in subterranean clover and to determine how these can be incorporated into new cultivars. Currently, a study is in progress to investigate the possibilities of using tissue culture techniques in subterranean clover improvement (Tan 1983).

The present philosophy in the NSCIP is that increasing subterranean clover's overall contribution to pasture and crop production can best be achieved by developing cultivars (low in oestrogenicity) which are better adapted to the wide range of environmental and management regimes that occur. It seems appropriate that the emphasis on adaptation should be maintained in the immediate future.

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Discussion

Stern: In Australia where subclover forms part of the wheat sheep farming system, N fixation and the N contribution to the soil are as important if not more important than clover for grazing purposes.

Roughley: Very little sown subclover is now inoculated in Australia. Generally indigenous strains of clover Rhizobia are poorly effective

relative to the selected inoculant strain. It is important that the new cultivars produced have improved Rhizobia associated with them, to reduce competition from poor strains of Rhizobia present in the soil. This may be approached by selecting for less promiscuously nodulating hosts.

Lancashire: High oestrogen types tend to be less well grazed in a free choice situation. This could introduce a bias in evaluation in grazing trials.

Collins: Yes, this could be a problem. It tends to be minimal, however, as most plants evaluated are low in formononetin.

Easton: How do you determine the balance between maximum seed production and perhaps longer vegetative growth and N fixation? Would growers accept reseeding pastures?

Collins: There have to be tradeoffs of course. I detect that growers may be prepared to consider reseeding some situations.

Sheath: The importance of the seedbank has only recently been demonstrated. In pumice country, only legumes which set hard seed were present after a number of years...there had obviously been a large turnover in plants.

I am concerned when it comes to using Australian subclovers in a situation where there is high grazing pressure. Selection processes in Australia are based on ecological adaptability rather than "grazeability." In our situation such plants often do not persist as well as those to which grazing had been applied as a selection pressure.

Collins: A conflict between persistence and production has always existed, and, with subclover, it will continue to be a problem.

Breeding Leucaena

R.A. Bray[1]

Abstract

This paper considers plant improvement of Leucaena in the widest sense. The available genetic material is summarised in the context of present taxonomic thought. The development of L. leucocephala in Australia is traced from early evaluation of a small collection through the development of cv. Cunningham and breeding programmes aimed at reducing mimosine content. The potential of interspecific hybrids is emphasized. The major limitation to further usage of leucaena is its acceptance by graziers, although establishment and potential toxicity can also be problems. Future research needs to define accurately the environmental and edaphic constraints to the use of leucaena and evaluate the existing large collections. Information on correlations between seedlings and adult trees is needed, as is information on the extent and nature of genotype x environment interaction.

Introduction

Leucaena leucocephala (family Mimosaceae) is a leguminous shrub or tree, with its centre of origin in Mexico and Central America. It has a long history of exploitation in its native environment, mainly as a source of browse fodder, or as a cut-and-carry feed. For several hundred years, it has been widely dispersed throughout the tropics, probably as a result of voyages of Spanish ships from Mexico.

There has recently been a great deal of interest generated in leucaena (see, for example, National Academy of Sciences 1977), not only as a forage plant but also as a source of firewood, wood chips, etc. In this paper, I will restrict myself almost entirely to its use as a forage plant, since this is its sole Australian use.

Leucaena prefers alkaline, well-drained soils, and grows best under warm conditions, although it is not killed by light frosts. Given good growing conditions, very high yields of good quality forage can be obtained, with figures of over 20 t ha^{-1} yr^{-1} being recorded. However, in Australia a figure of 2 to 4 t ha^{-1} yr^{-1} of edible dry matter (leaf plus small stems) would be more usual over much of the seasonally dry areas where it is grown. This yield, while not great, is generally higher than can be achieved from most other forage or browse legumes in those environments. Leucaena contains the toxic amino acid mimosine, an antimitotic agent. In ruminants, mimosine is degraded to 3-hydroxy-4(1H) pyridone (or DHP), a potent goitrogen. Thus the use of leucaena has sometimes been restricted by concern regarding its toxic properties.

Here I will consider "breeding" in its widest sense, encompassing plant improvement as a whole and including selection procedures and evaluation. I will consider what genetic resources are available, and how they might be used, in the light of past work and current perceived limitations of leucaena.

Available Genetic Resources

Although in the past, research and development have concentrated almost entirely on L. leucocephala, it is likely that in the future more use will be made of other species in the genus. The composition of the collection held by the CSIRO Division of Tropical Crops and Pastures, and other pertinent information, is shown in Table 1. Many of these accessions were collected by Mr. R. Reid in Mexico during 1979-80.

The ten species listed represent the taxonomic range described by Brewbaker (1983). Previous classification (Britton and Rose 1928) divided Leucaena into over 40 species. In our collection there are numerous accessions which do not readily fit into the 10 species recognized by Brewbaker (1983). Many of these accessions would be classified as L. diversifolia by Brewbaker's system. However, some may yet prove to be sufficiently distinct to be accorded species status. In particular, a large group show affinities with L. paniculata Britton & Rose, and several accessions with high (ca. 112) chromosome numbers, collected in eastern Mexico show affinities with both L. diversifolia (Schl.) Benth. and L pulverulenta (Schl.) Benth. The larger leafed species (L. lanceolata, L. macrophylla, and L. trichodes) seem to intergrade throughout their range of distribution. Hybrids may readily be made between most species (Brewbaker 1983, Hutton 1983) and may account for some of the taxonomic confusion.

A knowledge of chromosome numbers of the various species is necessary as a prerequisite for a breeding program. L. leucocephala has 104 chromosomes and forms 52 bivalents at meiosis. L. pulverulenta is apparently isolated with 2n=56, as most other species are reported to have 2n=52. However, I have been unable to confirm the latter, as meiotic counts almost invariably contain more than 26 bivalents.

Brewbaker (1983) has discussed the breeding systems of various Leucaena species. In his opinion, only L. leucocephala is self-compatible, and this self-compatibility is the result of a breakdown of the incompatibility system due to a high order of polyploidy. He also theorises that in some self-incompatible "diploid" species (2n=ca. 52) such as L. diversifolia, plants with higher chromosome numbers (2n=ca. 104) should be self-fertile. This appears to be correct, as I have found several accessions of L. diversifolia (including K155 and K186) to have more than 100 chromosomes and to set much more seed than "diploid" types of L. diversifolia.

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Table 1 - Details of the Leucaena collection held by CSIRO Division of Tropical Crops and Pastures

Species	No. of accessions	Main area of collection	Likely usage[1]
L. esculenta	8	Central Mexico	Human food (pods).
L. diversifolia	13	Mexico	Wood production; cool climates.
L. pulverulenta	39	NE Mexico	Low mimosine.
L. collinsii	6	Guatemala	Ornamental; shade
L. leucocephala	ca. 500	Yucatan	Marginal environments
L. shannoni	10	S. Mexico	Ornamental?
L. lanceolata	20	SW coast of Mexico	Acid soil tolerance?
L. macrophylla	32	SW Mexico	Forestry?
L. trichodes	14	Colombia	
L. retusa	5	Texas	Ornamental
Unknown or undetermined.	34		

[1]All species are browsed in their native environment, and therefore may have some potential as browse plants.

There are several other large collections of Leucaena in the world, with those in Hawaii and Flordia probably being the most extensive. Other significant collections are held in Colombia, Brazil, India, Taiwan, and the Philippines.

The Development of Leucaena in Australia

In the late 1950's and early 1960's, E.M. Hutton and S.G. Gray screened a relatively small collection of L. leucocephala, revealing a range of growth habits. Although most accessions were of the bushy, free-seeding type, others were erect and late flowering, and a few vigorous and well branched. This early work led to the release of three cultivars--El Salvador, an erect, non-branching type; Peru, a vigorous well-branched line with high levels of dry matter production; and Hawaii, the best of the weedy free-seeding types. Of these three, only cv. Peru has been a commercial success.

Cv. Peru and CPI (Commonwealth Plant Introduction number) 18228 (an erect line from Guatemala) were used by E.M. Hutton as parents in a breeding program that culminated in the release of cv. Cunningham. Cunningham was bred by conventional pedigree methods, with F_4 and later generations being grown at a wide range of sites. It was originally released at the F_6 stage. Cunningham, although generally less vigorous than cv. Peru in the establishment year, usually outyields it in later years. The mimosine contents of Peru and Cunningham are similar. Cv. Cunningham is the only bred variety (as opposed to selected) available in the world.

During the development of cv. Cunningham, it was decided to try to produce a cultivar with low mimosine content. To this end, the existing collection was screened for mimosine, and two accessions of L. pulverulenta were found with ca. 2% mimosine compared with ca. 4% in L. leucocephala. The L. pulverulenta accessions were crossed to "line 3" (which was later released as cv. Cunningham) and 55 F_1's selected for low mimosine and good vigour. Two generations of backcrossing to Cunningham followed, again with selection for low mimosine and good vigour. To this stage, seed had been produced only with difficulty, but among the 85 plants selected in the BC_2 generation were 26 which proved to have some degree of self-fertility. The availability of seed from these plants provided an opportunity to assess breeding progress in a field trial. Unfortunately, although the low mimosine selections did have lower mimosine contents than both cv. Cunningham and cv. Peru, they were not as vigorous as those cultivars. Consequently this aspect of the breeding program was discontinued. It is possible that further backcrosses to L. leucocephala may have restored a more nearly balanced chromosome complement; further backcrossing followed by selection among selfed progenies may

have produced high-yielding lines with lower mimosine contents than in the existing selections.

Another approach to the breeding of low mimosine lines has been the direct use of L. pulverulenta x L. Leucocephala F_1 hybrids (Bray 1984). Many of these hybrids are quite vigorous, and yields of up to 150% of that of Cunningham are easily achieved, with about 80% of the mimosine concentration. However, the early seedling vigour of these hybrids is not good, and seed production needs special techniques.

Since the initial evaluation of the collection in the 1950's, many new introductions have become available. Some of these were tested in a multisite trial and showed superiority to cv. Cunningham over a three-year period (R.A. Bray and D. Cooksley, unpublished data). Some results are shown in table 2. CPI 58396, a multibranched leafy type introduced from the Botanic Gardens in Barcelona (Spain), seems to have the greatest potential. CPI 61227 from Campeche (Mexico) is also extremely promising.

One feature of this trial was the good forage production of the American cultivar K8. This was originally selected as a non-branched type suitable for wood production. However, under regular cutting, it produced forage yields generally greater than cv. Cunningham, even though it produces fewer branches. It is evident from this and other studies that classifications based on branching habit can readily be modified by management practices. Thus new introductions should not be too stringently categorised. (Although it is possible that non-branched "timber" types may well prove to be satisfactory grazing plants, the converse is not true, since no management practice can suppress branching of a well-branched type without also restricting plant size. Well-branched types may of course still be useful sources of smaller wood for cooking, etc.)

Table 2 - Total edible dry matter production of four lines of L. leucocephala, grown at three sites, for two years

Lines	Edible dry matter (t ha^{-1}) for sites at[1]--		
	Gayndah	Lansdown	Kairi
cv. Cunningham	4.8	9.5	11.9
cv. K8	5.8	10.3	15.7
CPI 58396	6.7	12.1	16.4
CPI 61227	6.8	9.8	16.1

[1]Gayndah located 25° 36'S, mean annual rainfall 762 mm; Lansdown 19° 40'S, M.A.R. 898 mm; Kairi 17° 13'S, M.A.R. 1260 mm.

There are many more recent introductions that have only been evaluated under nursery conditions. Since many of these come from the Yucatan Peninsula and other areas known to harbour extensive variation, it may be anticipated that some interesting and novel genotypes will be discovered.

Current Limitations to the Use of Leucaena

Establishment

In Australia, establishment is considered by some to be the major factor restricting the increased usage of leucaena. Although there can be no argument that leucaena seedlings are at first relatively slow growing, very susceptible to weed competition, and generally slow to nodulate, there are techniques (Cooksley 1982) that lead to adequate establishment. While improved ability to establish would be a decided advantage for future cultivars, it is not essential. Potential users of leucaena must accept that, being a tree, its establishment will be slower than conventional pasture legumes. Since protection of young seedlings from grazing is essential, considerable effort and expense is necessary for successful establishment.

Is it possible to breed for improved establishment? There are a number of characters which affect establishment, and before any breeding or selection is undertaken it is essential to determine which of these characters are important and what genetic variation exists. Some obvious ones are seed size (see below for discussion), rate of germination, seedling height (possibly growth rate), leaf area, rate of nodulation and/or association with mycorrhizae, etc. If it can be established that any one (or a few) character is mainly responsible for improved establishment and that variation for component characters exists, then selection should be possible. Studies are in progress to determine firstly whether lines with known differences in seedling vigour exhibit differences in their ability to establish, when grown together, and secondly, which particular characters are important.

Toxicity

Although the potential toxicity of leucaena due to mimosine (and DHP) is well known, it is probably not a serious problem in the farm situation. Only rarely are clinical signs of mimosine or DHP toxicity observed in grazing ruminants in Australia; however, it is probable that liveweight gains are reduced even at subclinical levels of mimosine/DHP (Jones and Winter 1982). Management strategies aimed a keeping leucaena below 30% of the diet should minimise any ill effects.

Recent developments in the isolation and introduction of bacteria that can degrade DHP in the rumen (Jones 1981) suggest that a biological solution to the problem may be at hand, at least in cattle and goats. As discussed earlier, there is little prospect at present of breeding a cultivar with really low mimosine content. This is a classic

case of plant breeding being overtaken by technology and management--even if a low mimosine line had been available, it would have been unlikely to have been a commercial success in the cattle industry, given the promise of the new bacterial approach.

Nevertheless, the problem of toxicity remains for feeding leucaena to non-ruminants--especially pigs, chickens, and fish (and also humans; with potential seed yields of several t ha^{-1}, this use can hardly be ignored). Although simple treatments such as hot water will reduce levels of mimosine in leaves, this may be of little practical use since the mimosine is merely converted to DHP (Lowry 1983).

The main difficulty in selecting for low mimosine is in the precision of sampling. Mimosine content of leaves declines rapidly with leaf age and is also affected by factors such as moisture stress (Bray and Hoekstra, unpublished data). There is little correlation between seedling mimosine content and that of adult trees (Bray 1984), unless the population sampled covers a very wide range of mimosine concentrations. Screening of seedlings is further complicated by the fact that mimosine content is at its lowest in the first formed leaves (R.A. Bray, unpublished data). Our usual method of sampling adult trees (the "second expanded leaf") consistently has a c.v. of about 15%-20%. Repeated sampling of plants in comparable phases of growth is necessary for accurate assessment of mimosine content.

Environmental Limitations

Being a tropical or sub-tropical plant, leucaena does not flourish in cool climates, nor in arid environments. However, once established, it can often survive quite well in dry areas, although leaf loss may be severe. The array of germplasm now available suggests that it might be possible to select lines more suited to cooler and drier areas than the current cultivars.

In many overseas countries, growth of leucaena is severely retarded in acidic soils. The precise cause of this poor growth is unknown, although it is probable that aluminium (in excess) and calcium deficiency are both implicated. Any breeding for tolerance to these acid soil conditions must first address the question of why growth is so poor in these soils, in order to provide a sound basis for selection.

Seed Production

In some countries, seed production of selected lines of leucaena has been considered to be poor. There are several reasons for this: (1) the naturalised weedy strains produce copious quantities of seed on a relatively small bush; (2) selected types are generally later flowering and in fact produce less seed; (3) selected types are more vigorous, and pods are often carried some meters from the ground. In addition, shattering is common, and harvesting must be carried out on several occasions.

These problems are probably not amenable to solution by breeding, but the development of suitable management strategies, using stands specifically grown and managed for seed production, should enable adequate seed yields to be obtained, at a price that will not deter potential purchasers. (The current Australian price of ca. \$35 kg^{-1} almost certainly has such a deterrent effect. It is of interest to note that developing countries can market similar seed at less than \$1 kg^{-1}).

Pests and Diseases

It is perhaps inaccurate to include this heading under "Limitations," since leucaena is remarkably free of insect pests and important diseases. In Australia, the only problem of note is the presence of a moth *Ithome lassula* (Common and Beattie 1982) the larva of which attacks young inflorescences. The importance of the problem is not known, but severity of attack varies throughout the year, and some species (those with more open flowerheads) suffer less damage than others. This insect apparently occurs worldwide in all leucaena-growing areas but seems not be of major importance.

Termites can cause severe damage to young trees, especially when transplanted. It is not known if variation exists for resistance to this type of attack.

There are no diseases of importance in Australia. In India, there is considerable concern regarding "gummosis", a disease apparently caused by *Fusarium semitectum*, which is threatening the economic potential of leucaena in that country. It has not been recognised as a problem elsewhere.

Future Research Needs for Improving Leucaena

It is obvious that, as in all plant improvement programs, objectives for improvement must be clearly defined. Not only must the desired end result be clear, but also the particular means of achieving that result--e.g., tolerance to low levels of calcium as a means of achieving better growth in acid soils or quicker nodulation to achieve better establishment.

From an Australian point of view, the main objectives are: increased range of adaptation, especially into cooler climates; higher yield throughout the year, particularly with reference to retention of leaf through the dry season; and better establishment.

In the long term, usage of leucaena may be limited by factors that cannot be overcome by breeding or selection--in particular, acceptance by the grazing community of the need for special management practices, both in the seedling stage (protection from weeds and predatory grazing) and later when being utilised by cattle.

Because leucaena is a perennial, it is both desirable and necessary to be able to select superior plants as early as possible. It has become clear that seed size itself is a good indicator of potential tree vigour (Brewbaker et al. 1972). In our collection at Townsville, accessions with seed weights of above 50 mg generally show the most vigour as adult trees. Obviously this criterion is of value when dealing with unknown genotypes or a large collection.

Seedling development also provides a guide to the subsequent growth habit of the tree (Bray 1980) in that the more vigorous types tend to produce leaves with more than one pair of pinnae earlier than less vigorous, weedy types. Thus seed size, seedling development, and a knowledge of the origin of an accession can together provide useful criteria for retaining or discarding an accession.

Little is known about correlations between other seedling characters and those of the adult trees. Certainly, mimosine content of seedlings is not well related to that of adult trees (r_g=0.29, Bray 1984). In addition, growth of seedlings often does not accurately predict later yield. In one glasshouse experiment, various selected lines outyielded cv. Cunningham at 12 weeks of age but were inferior later in the field (R.A. Bray, E.M. Hutton, and W.M. Beattie, unpublished data). It is also common for cv. Peru to outyield cv. Cunningham in the first year but for Cunningham to overtake it later.

A knowledge of which characters are essential in a vigorous perennial plant, and how these characters might be recognized in seedlings, would be valuable. Correlation between seedling and adult characters should be further investigated to enable indirect selection in the seedling.

How should the available genetic variation be exploited in a breeding program? In past programs, Cunningham was developed by the conventional pedigree method (Mackay 1981), while the low mimosine program used backcrossing (R.A. Bray, E.M. Hutton and W.M. Beattie, unpublished data). There is no reason to suspect that the conventional methods of breeding self-pollinated plants would not succeed, although genetic advance may be slow because of polyploidy.

One of the major opportunities for plant improvement lies in the use of interspecific hybrids (Brewbaker 1983, Bray 1984). Propagation of these would probably have to be by cloning (cuttings) or even tissue culture, although it may be possible to produce sufficient F_1 seed by appropriately arranged incompatibilities or by controlled outcrossing. I have set up a small seed production area for the production of F_1 L. pulverulenta x L. leucocephala hybrids, using L. pulverulenta scions grafted onto L. leucocephala stocks to provide vigorous "female" plants. Pollen is provided by cv. Cunningham planted in alternate rows. Seed is harvested only from the L. pulverulenta parent. So far several hundred grams of seed have been produced, and work is under way to determine what proportion of this is hybrid seed. Hybrids between other species should also be investigated.

The nature and extent of genotype x environment interaction needs clarifying. There are indications from field trials (R.A. Bray and D. Cooksley, unpublished data) that amongst high yielding varieties, the G x E interaction may be substantial. The importance of this interaction may influence evaluation of new cultivars.

Conclusions

It is clear that, with the large collections of L. leucocephala available, much improvement should be possible simply through screening of accessions. Breeding may be unnecessary, except where no accession with all the desired features can be found.

Interspecific hybrids offer great promise, especially for wood production, although special techniques for seed production and/or propagation may be necessary.

The task of selecting promising new lines is made more difficult by the perennial nature of the plant and the large plot sizes needed. The development of methods for accurate selection on young trees would greatly facilitate improvement procedures.

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Discussion

Marten: No one has talked about Sesbania. Do you have information?

Bray: There is a sizable and well-described collection of Sesbania, but it is largely an unpalatable plant.

Rumbaugh: A student is investigating, in a greenhouse, seedling growth problems under three levels of irrigation. There appears to be no establishment problem with adequate water.

Bray: Leucaena is slow to nodulate--in some cases 56 days. There are areas in Africa where this lag in establishment does not occur, but we do not know what soil or environmental factors are responsible.

Helyar: Will leucaena grow under low rainfall?

Bray: Yes, down to about 750 mm annual rainfall, provided you can get it established.

Sheath: What management developments are necessary to use leucaena?

Bray: Potential users must appreciate the need for adequate care during establishment to minimize weed competition. Also, they must be prepared not to graze it until about 1 metre high and be prepared not to get much return from it for the first season. Once established, there is a choice of management systems—one of the simplest involves planting an area of leucaena adjacent to areas of native grassland and making sure that animals graze both grass and legume.

Clements: The problem mentioned earlier of merchandising a "leucaena package" to farmers--would you care to comment? Are there newer types that it may be easier to encourage farmers to use?

Bray: I feel that we probably don't need to breed more material—the problem lies in changing farmer attitude to management. I don't believe we can improve "establishment" by an order of magnitude and that considerable care and patience will always be needed.

The Touch of Man

Drops of dew covered the stand
until disturbed by a caring hand.

He knelt there in the morning sun
examining each plant knowing much needed done.

The energy flowed in the leaves of green
forcing growth not easily seen.

He adjusted his hat to tilt the brim
to shade his eyes from the rays coming in.

He pondered the role this plant must play
as he knelt in the field on that sun-laden day.

The duff he cleared and withdrew a plug
and exposed a structure that housed a bug.

A special relationship, needless to say,
from the plant it took life but gave nitrogen some way.

He pondered in mind a relationship so great
that a plant would give life for nitrogen sake.

This process has existed for decades gone by
but the world has really not determined why.

Scientists gathered over the past five days
to discuss and discover the legume's magic ways.

The topic was cast and time brought to a stop
as they gathered together for a trilateral workshop.

The Aussies, the Yanks and the Kiwis too
spent a week on this topic to decide what to do.

Debate, it did flourish, it was a marvellous show,
Persistence was highlighted but the nasties must go.

The grazing of beast finally interrupted his trance,
and he rose to his feet from his kneeling stance.

The sun had now risen several meters in the sky,
and cast the shadow of a giant of a guy.

He left the field to begin his day,
to ponder God's gift in his workshop of play.

The beast grazed on and the sun moved to the peak
and the footsteps of man soon disappeared in the heat.

Yet, the touch of man cannot be denied,
Legumes live now where before they died.

Joseph C. Burns